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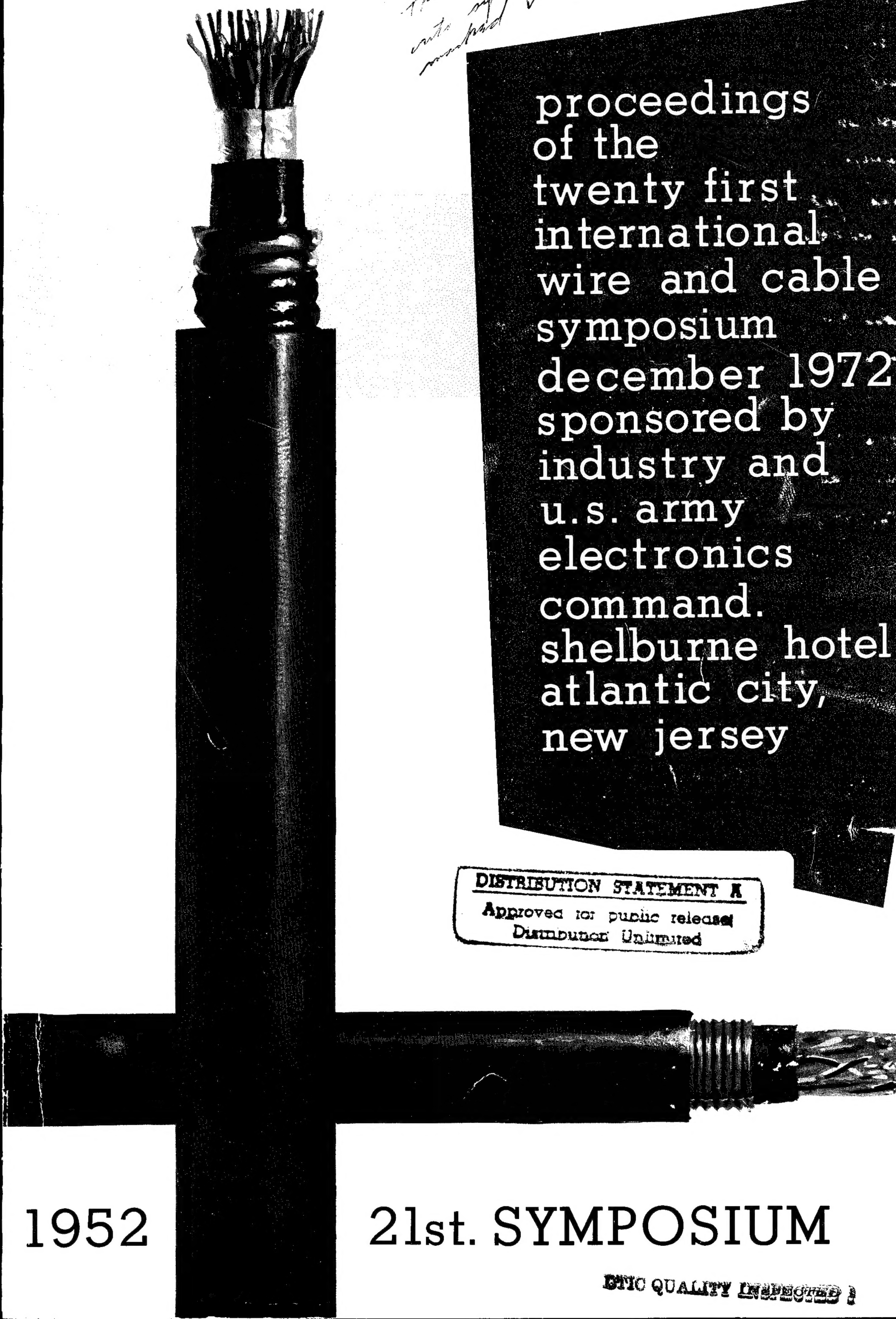

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21st INTERNATIONAL WIRE AND CABLE SYMPOSIUM

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Clyde Hatch, Naval Ship Engineering Center

TECHNICAL SESSIONS

Tuesday, 5 December 1972

10:00 a.m. Session I:	Tutorial Session on Multipair Cable Design and Shielding (Note: Lectures will not be published)
2:15 p.m. Session II:	Special Cables for Marine Applications and Advanced Systems

Wednesday, 6 December 1972

9:15 a.m. Session III:	Environmental Effects and Protection of Telephone Cable
2:15 p.m. Session IV:	Wire Materials and Terminations
2:15 p.m. Session V:	Cable Manufacturing Methods

Thursday, 7 December 1972

9:15 a.m. Session VI:	Communication Cable and Sheath Design
9:15 a.m. Session VII:	Coaxial and Multiconductor Cable
2:15 p.m. Session VIII:	Cable Materials

PROCEEDINGS

Responsibility for the contents rests upon the authors and not the Symposium Committee or its members. After the symposium all the publication rights of each paper are reserved by their authors, and requests for republication of a paper should be addressed to the appropriate author. Abstracting is permitted, and it would be appreciated if the symposium is credited when abstracts or papers are republished. Requests for individual copies of papers should be addressed to the authors. Extra copies of the Proceedings may be obtained from the Symposium Co-Chairman (Requests should include a check for $7.50 per copy, made payable to the Shelburne Hotel). Copies may also be obtained for a nominal fee from the National Technical Information Service (NTIS), Operations Division, Springfield, Virginia 22151.

Copies of papers presented in previous years may also be obtained from the National Technical Information Service. Papers from the first 20 years, with their AD numbers are cataloged in the "KWIC Index of Technical Papers, Wire and Cable Symposia (1952-1971)," December 1971.

MESSAGE FROM THE CO-CHAIRMEN

We were most gratified that the Twentieth Symposium proved to be such a notable success in so many ways. As with all anniversary celebrations, there was the convivial warmth of old friendships mixed with the nostalgia of the early days, and finally the honoring of the charter members of the first symposium committee. The committee received many kind letters from those who could not attend but wished to be remembered--particularly one from that grand patriarch of the cable industry, Sam Rausch.

Attendance at tutitorial sessions was overwhelming and prompted the committee to retain this feature on the program. This year, your committee is also trying parallel technical sessions, to permit inclusion of as many as possible of the excellent technical papers submitted. Your comments are solicited on this new format.

This year also marks a shift in the committee lineup. Mr. Jack Spergel, who has joined the staff at General Cable Corporation, will step down after nine years of outstanding, dedicated service as co-chairman. He will, however, continue his active and innovative participation as an industry member on the symposium committee. Mr. Elmer Godwin, our long time associate at ECOM, will fill the vacancy left by Jack.

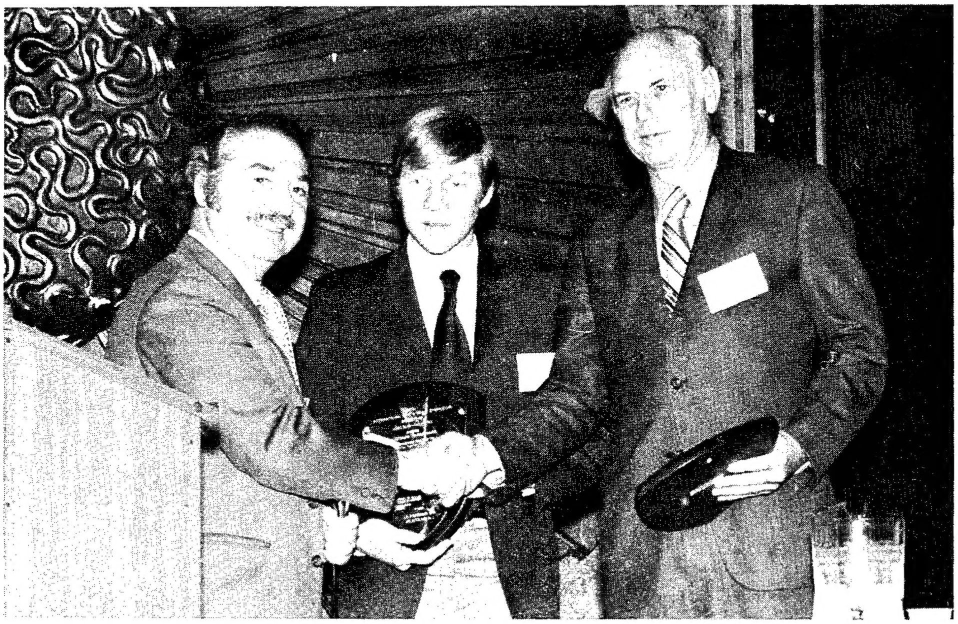
We look forward to the continued enthusiastic support by members of the Wire and Cable Industry, and the dedicated efforts of our committeemen to sustain these highly successful symposia in the years to come.

Milton Tenzer
Jack Spergel

HIGHLIGHTS OF THE 20th INTERNATIONAL WIRE AND CABLE SYMPOSIUM

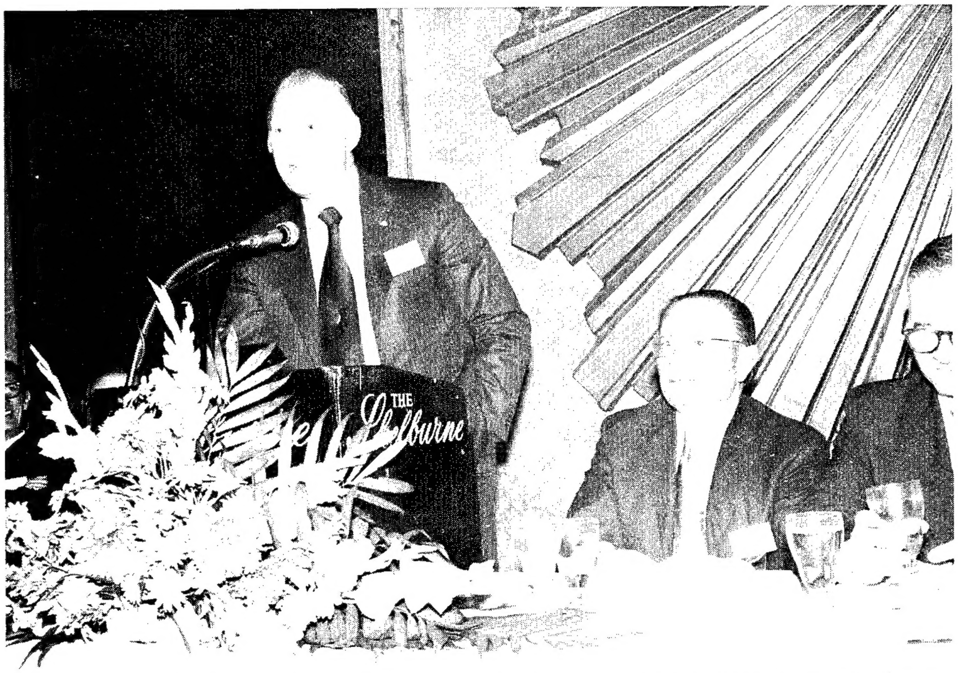
Nov. 30, Dec. 1 and 2, 1971

Shelburne Hotel, Atlantic City, N. J.



David Setzer and Alfred Windeler, both of Bell Laboratories, receiving the award for the Outstanding Technical Paper of the 19th IWCS, entitled "A Low Capacitance Cable for the T2 Digital Transmission Line."

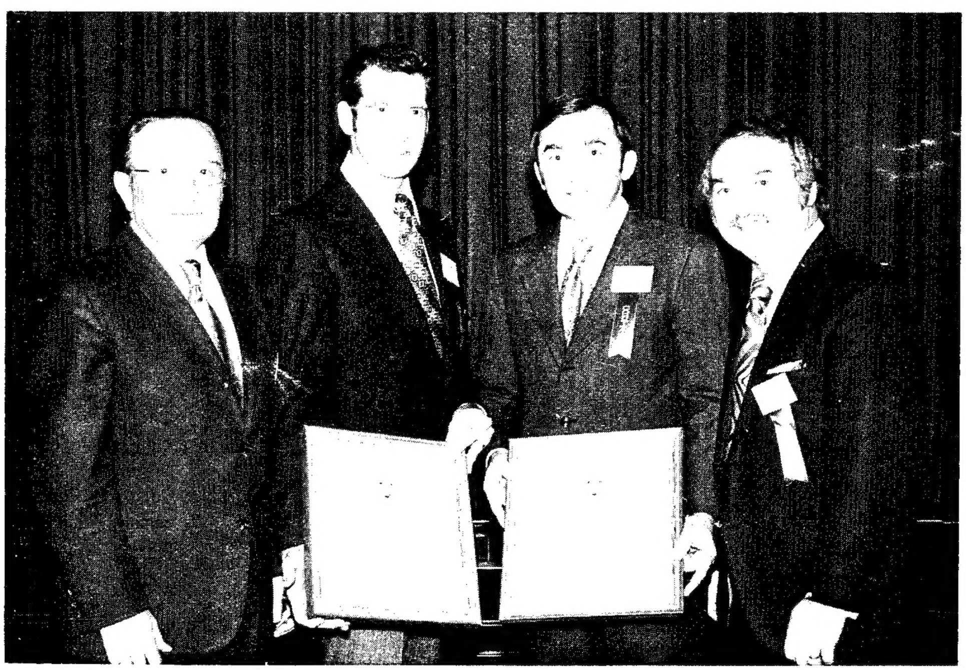
Dr. Ottmar Leuchs, Kabel-und-Metalwerke, receiving the award for the Outstanding Presentation of a Significant Technical Paper at the 19th IWCS entitled, "A New Flame Self-Extinguishing Hydrogen Chloride Binding PVC Jacketing Compound for Cables."



COL H. Priddle, White House Communications Agency, delivering address on "Presidential Communication," at the banquet.

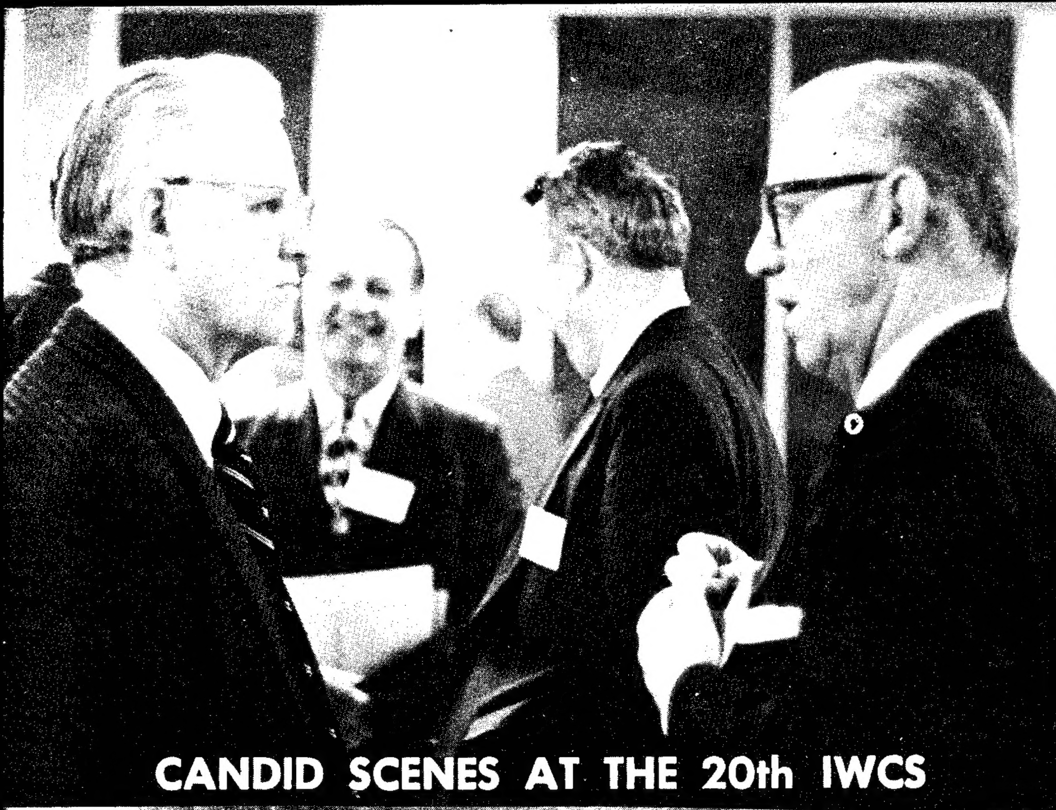
Members of the 1st Symposium Committee being honored at the 20th Anniversary of the IWCS. From left to right: T. F. Scoville, M. Lipton, H. Kingsley, F. Wills, H. Weber, and M. Tenzer.

F. Horn being presented with a radio and plaque by J. Spergel on the occasion of his retirement from Bell Laboratories after 40 years of service. He also served on IWCS Committee for 10 years.



Committee members, G. A. Lohsl, Hatfield Wire & Cable, and D. Stewart, Phillips Petroleum, receiving their Certificates of Appreciation from the Co-Chairman for their service to the Symposium.

CANDID SCENES AT THE 20th IWCS



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Chairman: S. F. Luques, Brand-Rex Co.

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SESSION VI—Communication Cable and Sheath Design

Chairman: J. D. Kirk, Alberta Government Telephones

MECHANICAL ASPECTS OF SUBMARINE TELEPHONE CABLE SYSTEMS

C.F.G. Smith and F.L. Jarvis

Standard Telephones & Cables Ltd.,
London, England.

SUMMARY

Submarine telephone cable systems used for inter-continental communication are expected to have a minimum operating life of 25 years. Mechanical reliability is therefore of paramount importance since a number of associated parameters affect the short and long term transmission performance of the system. Following background information, ocean survey, cable types, repeater housings, corrosion aspects and laying methods are described briefly.

INTRODUCTION

Although long distance telegraph cables have been in existance for upwards of a century it is not generally realised that long distance submarine telephone cables permitting person to person conversations have been in service for less than 20 years. A leading article in The Times giving news of the successful laying of the first telegraph cable across the Atlantic in 1858 commented on the day after completion: "Mr. Bright, having landed the end of the Atlantic cable at Valentia, has brought to a successful termination his anxious and difficult task of linking the Old World with the New, thereby annihilating space. Since the discovery of Columbus, nothing has been done in any degree comparable to the vast enlargement which has thus been given to the sphere of human activity". The successful first Transatlantic telephone cable[1] laid in 1956 had predictably less impact on a technologically oriented world. The latter system provided 36 speech circuits and employed two cables, one for each direction of transmission. Current long distance systems provide 1840 speech circuits employing a single co-axial cable for bi-directional transmission. Thus in the space of 16 years capacity has been increased by a factor of 100 using single cable systems as the basis for comparison.

Realisation of inter-continental telephone communication by cable was made possible by improvements to materials and processing technology for cable and device technology for repeaters which are amplifying devices used to compensate for signal attenuation in the cable. The repeaters, coupled at intervals into the cable, have a gain characteristic which compensates for the cable attenuation nominally given for frequencies above 50 KHz by the following equation:

$$= A \frac{\sqrt{K}}{D} \sqrt{f} + B \sqrt{K} \tan \delta f \qquad (1)$$

Where A and B are constants,
D is the dielectric diameter,
K is the permittivity of the dielectric,
δ is the loss angle of the dielectric
and f is the frequency of the signal.

The left hand term is dominant at low frequencies. Variations in its parameters change the level of the attenuation curve but not its shape. Such variations can therefore be offset by adjustment to the cable length between repeaters. At higher frequencies the right hand term becomes significant. Variations in dielectric loss change the shape of the attenuation curve and must be closely controlled since length adjustment will not give the desired attenuation over the full frequency spectrum. It should be noted that the repeater gain characteristic is constant for all repeaters manufactured for a given system. For single cable systems the repeaters contain directional filters so that low band frequencies are used for one direction of transmission and high band frequencies for the other. Present long distance systems have a top operating frequency of 14 MHz with repeaters coupled into the cable at intervals approximating to 6 nautical miles.

OCEAN SURVEY

Prior to survey of a particular route, all available charts and other pertinent information are researched to draw up a survey plan identifying items of critical importance affecting the basic objectives which concern transmission performance, safe physical placement and cable ship operations.

Detailed data on the ocean temperature and depth profiles over the complete route are determined and seasonal variations in temperature ascertained. Information on radio frequency sources and electrical storm activity adjacent to the respective terminals is studied. Since the cable and repeaters must be positioned to give substantial freedom from damage over the system life span, detailed evaluation of rugged sea bottom and continental shelf areas is made to avoid suspension of cable and repeaters as resultant chafing due to currents would lead to premature failure. Where possible, areas of fishing activity are avoided, but because of changes in fishing patterns success is sometimes limited. Care is taken to avoid areas of volcanic activity and near land, unstable silted areas adjacent to river outfalls. From the point of view of cable ship operations specific details on prevailing winds, currents and seasonal weather data are obtained. Slack allowances varying with the sea bottom topography are allocated to ensure that the cable conforms to the contours of the sea bed. Particular attention is paid to navigational accuracy and special action taken in critical areas to ensure that the cable is positioned as demanded by the survey results. Sea bottom core samples are taken at selected route points. Continuous testing may be carried out in shallow water areas amenable to ploughing operations in which cable is buried below the surface of the sea bed to avoid potential damage due to trawling activity. This technique has proved successful employing a vehicle designed by A.T.T. and used in conjunction with the Canadian cable ship C.C.G.S. JOHN CABOT.

SUBMARINE CABLE

Having specified the gain of the repeater at the top operating frequency, the data derived from the ocean survey is used to determine the cable types and precise repeater section lengths. The objective is to match the attenuation of laid cable to the repeater gain to an accuracy of approximately $\pm$ 0.1%. In the factory, transmission measurements are made at atmospheric pressure and a temperature of 10°C or thereabouts. Cable temperature, pressure and handling coefficients are applied to predict the attenuation and length of each repeater section in accordance with its position on the sea bed. It will be realised that a cable of exceptional mechanical stability is required to meet the transmission requirements whilst having adequate strength for laying and recovery operations. Particularly for deep water applications, the cable should be torsionally balanced under load so that on release of tension there is no tendency to throw loops.

From the earliest days the strength member of submarine telegraph cable consisted of armour wires helically applied over the cable core. This type of construction was continued for the early telephone cables, and, because of the need for shallow water protection, the use of various armoured cable designs is continued. For land sections and in water up to approximately 0.5 n.m. offshore soft iron screening tapes are applied over the co-axial structure to give protection against electromagnetic interference. Single and double layer armoured cables having breaking loads up to 140,000 lb (63,500 kg) are selected to suit the prevailing environment. Early deep water cables required single layer armouring to provide the necessary strength. Such a structure is not torsionally balanced, thus leading to serious problems during laying operations employing rigid repeater housings.

As bandwidths increased, cable core diameters were increased in accordance with the demand to optimise system cost. The dimensional increase and electrical skin effect at the higher frequencies together permitted a radical change to deep water cable design. Working independently, the British Post Office and Bell Telephone Laboratories positioned the strength member within the centre conductor structure, thereby eliminating external armour wires. These designs were termed LIGHTWEIGHT CABLE[2] in the former case and ARMOURLESS CABLE[3] in the latter. Both cables had an outer diameter approximating to 1.25" (31.75 m.m.) but exhibited a number of design differences. Whilst having the same overall diameter as the first Transatlantic cable, the dielectric diameters were increased from 0.620" (15.75 m.m.) to nominally 1" (25.4 m.m.). Cable attenuation and weight were therefore reduced relative to the former. For current systems both cable designs have been scaled up giving a dielectric diameter close to 1.5" (38.1 m.m.) with an overall diameter of 1.75" (44.5 m.m.)

Illustrations, Figure 1, show the cable designed by Bell Telephone Laboratories for the first Transatlantic telephone cable system and current British Post Office and Bell Telephone Laboratories designs. It is apparent that the simple structure of the latter types gives a significant improvement in cable mechanical and transmission performance. This, allied to developments in cable processing methods, permits manufacture of cable to consistent standards over thousands of miles whilst giving accurately

predictable characteristics when it is immersed in deep oceans where applied pressures may exceed 10,000 p.s.i. (7,031 tonnes/sq. metre).

As indicated in the simplified equation (1) given earlier, dimensional stability of the cable under handling and laying conditions is of paramount importance. Consequently all raw materials employed are purchased against specifications detailing precise mechanical, as well as electrical, characteristics.

The compact centre conductor structure does not change its dimensions under pressure. Its breaking load exceeds 17,000 lb (7,710 kg) as demanded by the weight, inertial and hydrodynamic drag conditions met with in cable laying and recovery operations. The tube welding operation is continuously monitored by eddy-current devices to ensure weld integrity. The centre conductor diameter is held to an accuracy of ± 0.001" (0.025 m.m.) on nominal at any point.

Special submarine cable grade polethylene is extruded tightly over the centre conductor and freedom from dielectric voids at rare weld pinholes ensured by a special cooling process[4]. Strength member joints consist of a steel ferrule swaged around the strand under strictly controlled conditions to give a minimum breaking load of 15,000 lb (6.800 kg). Injected polyethylene used to restore the dielectric at such positions must comply with rigid requirements, particularly over the parent/injectate amalgamation zone where 50 reverse bends around a 1" (25.4 m.m.) diameter mandrel must be achieved without partial fracture of the material.

Because the longitudinally formed return conductor must be continuously supported to give a satisfactory cable bending performance, the dielectric is shaved following extrusion of the dielectric. Opportunity is taken at the same time to servo-control the concentricity of the centre conductor. In the case of the 1.5" (38.1 m.m.) cable the core diameter is held to ± 0.001" (0.025 m.m.) on nominal at any point and the conductor eccentricity relative to the outer surface to not worse than 0.005" (0.13 m.m.).

The return conductor and plastics sheath are applied in a tandem operation requiring critical control. For mechanical reasons the return conductor must be in intimate contact with both the dielectric and the plastics sheath. This is critically important also from the standpoint of transmission characteristics since dimensional changes during handling and laying would be accentuated if the return conductor was slack over the dielectric, thus leading to significant and unacceptable changes in attenuation between factory and sea bed. Additionally, any water entering space between the dielectric and return conductor due to sheath damage or cable to repeater termination design will modify the dielectric characteristics leading to increase in attenuation. Bearing in mind that the objective is to predict laid cable attenuation to an accuracy of 0.1% it is obvious that all possible precautions must be taken. Completed 1.5" (38.1 m.m.) cable must be capable of withstanding 50 reverse bends around a 4.5 ft. (1.37 m.) radius to give an adequate margin of safety against normal handling during ship loading and cable laying. Dimensional changes resulting from flexing must be minimized by control of raw material characteristics and processing methods. Under tensile loads approximating to 16,000 lb (7,260 kg) the cable rotates less than one turn in 120 ft. (36.6 m.). Since during laying and recovery operations the cable is gripped from the outside, interlayer keying is required to transfer tensile loads from the sheath to the central stranded strength member. Thus each cable section produced is tested to ensure that specified interlayer adhesion values are being met. These vary with cable type but may typically be 80 lb per inch (1.4 kg/m.m.) length.

It will be appreciated that the foregoing covers only a few of the exhaustive inter-stage and final cable tests which apply during the course of routine manufacture.

Following transmission and allied electrical measurements the cable is "terminated" and stored in large pans or tanks to await collection by the cable ship. The terminations are of two basic types which perform the functions of transferring tensile loads to the repeater housing whilst maintaining co-axial connection to the repeater and guarding against water ingress. In the case of British Post Office systems short armoured tails are applied to LIGHTWEIGHT CABLE thus acting as a grip to transfer tensile loads. An illustration is given in Figure 2. ARMOURLESS CABLES designed by Bell Telephone Laboratories employ a gimbal coupling in which load is transferred directly from the centre conductor to the repeater housing.

SUBMERGED REPEATERS

There are two main factors which must be considered in the design of a submerged repeater. Firstly, it must operate satisfactorily in ocean depths where the water pressure must be reckoned in terms of tons per square inch; the repeater proper must therefore be enclosed in a pressure-resisting housing. The housing must be equipped with water-tight glands to enable connection to be made between the cable and the repeater and it must also be capable of being laid on the sea bed by means of the cable during the cable laying operation. The second main factor arises because of the impossibility of making

adjustments or carrying out maintenance on the repeater once it has been laid. Furthermore, replacement of a faulty repeater could be an extremely expensive operation not to mention the loss of revenue incurred during the period that the cable system was out of service. Utmost reliability must therefore be achieved in the design and manufacture of the repeaters and their pressure-resisting housings. The aim is to achieve a fault-free life of at least 25 years.

Submerged repeaters can be regarded as consisting basically of two parts:

(a) a repeater capsule i.e. the repeater proper, designed to provide the required amplifying characteristics and

(b) an outer pressure-resisting housing designed to withstand the pressure of sea water on the route over which the submarine cable is to be laid.

The electrical components and networks of the repeater capsule are assembled in separate apparatus units, each unit performing a specific electrical function. Methylmethacrylate bars support the apparatus units and are supported at their ends by circular brass closure plates; the whole assembly is enclosed in a brass tube which is sealed to these end plates. The closure plates also carry moisture-tight glands for entry of the connecting cables. The completed repeater capsule is filled with dry nitrogen before sealing. In order to reduce the risk of subsequent failure, all assembly and wiring operations on the apparatus units and the repeater capsule and the insertion of the capsule into the pressure-resisting housing are carried out under conditions of scrupulous cleanliness in special screened areas that are air filtered and temperature and humidity controlled. Furthermore, all those points in the manufacturing process that can affect the integrity of the finished repeater are given visual and electrical inspection on a 100 per-cent basis.

The pressure-resisting housing is of the rigid cylindrical type in which the end closures are cylindrical bulkheads fitted with water-tight glands which carry the electrical connections between the repeater capsule within the housing and the sea cables. It is designed to be laid "in line" with the cable i.e. the cable entries are at opposite ends of the housing.

The points at which it is necessary to seal against the entry of sea water are therefore:

(a) At or through the cable glands

(b) Between the bulkheads and the casing

(c) At any subsidiary entry through the bulkheads required, for example, for filling the housing with dry inert gas.

The cylindrical bulkheads may be welded or brazed in position or alternatively made de-mountable by use of O-rings which are a well proven means for sealing against fluid pressures of up to several tons per square inch. Ensueing comments are restricted exclusively to the latter technique. By its very nature, however, an O-ring only becomes really effective as a seal as it becomes subjected to the fluid pressure against which it is required to seal. Therefore in the case of a submerged repeater, where it is essential that the effectiveness of the sealing should be proved before finally committing the repeater to the ocean depths a number of problems can be foreseen. In repeaters supplied by Standard Telephones & Cables Ltd., objections to the use of simple O-rings have been overcome by providing for the O-rings to be continuously subjected to a fluid pressure which will oppose, and be greater than, the ultimate sea-pressure[5]. This is accomplished by using as a seal, two O-rings between which a viscous fluid (petroleum jelly - P.J.) is forced and held at a pressure in excess of the highest sea-pressure the seal will have to sustain. Means are provided to check that the pressure between the O-rings, initially set in the factory when the housing is sealed, is maintained and this check can be applied at any time, even to within a few minutes of committing the repeater to the sea.

Such a check is equivalent to a pressure test far greater in length of time than any practicable factory external pressure test and secondly, since the pressure on the O-rings is never released, it eliminates any change in their deformation under successive applications of pressure. Thirdly, the quantity of fluid under pressure (the P.J.) is small compared with the large quantity required for an external pressure test and therefore the sensitivity to a drop in pressure, which would indicate a leak in the seal, is greatly enhanced.

The practical embodiment of the pressurised O-ring seal is covered by the following description of the pressure-resisting housing. The housing was developed initially in conjunction with Messrs. Vickers Armstrong; refinements were added as a result of further development, some of which was carried out in conjunction with the British Post Office.

In principle, the housing consists of a high-tensile-steel tube or casing with its ends closed by high-tensile steel bulkheads sealed into the casing by means of special hard-grade synthetic rubber O-rings which are forced against their seatings by

means of the pressure of petroleum jelly between them. The overall dimensions of the housing are; diameter, 10.5 inches (27 centimetres) and length, approximately 9 feet (270 centimetres). It is suitable for laying in depths of water up to 3500 fathoms (6400 metres); this is equivalent to a pressure of sea-water of just over 4 tons per square inch (360 kg per square centimetre).

Figure 2 is a sectional view of one end of a pressure housing showing the sealing of the bulkhead and the anchoring arrangement for the end of the sea cable, (the other end of the housing is identical). The space within the end of the housing up to the outer face of the bulkhead is open to the sea. The bulkhead, which is a close fit in the casing, has two main O-rings carried in grooves round its periphery. The space between the rings is connected via small radial holes with two cylinders bored into the bulkhead from the outer face.

The enclosed space formed by the two main O-rings and the sealed-off cylinders is filled with petroleum jelly, the jelly being compressed to a pressure of 4 tons per square inch (630 kilogrammes per square centimetre) at an ambient temperature of 22 degrees centigrade by means of the pressurising piston and its pressure screw in the upper of the two cylinders shown in figure 2.

The lower of the two cylinders in the bulkhead is sealed-off by means of two pistons, the inner piston being in contact with the petroleum jelly and the outer piston, which has a larger diameter, being exposed to the sea. This arrangement provides a pressure-intensifying device for the petroleum jelly system. The ratio of the piston areas is 1.36:1, thus even though the pressure in the system may have fallen well below the initial setting of 4 tons per square inch (630 kilogrammes per square centimetre) due to the pressure/temperature coefficient of the petroleum jelly, the device will automatically raise the pressure in the system when the repeater is laid in the sea, to at least 1.36 times that of the external sea-pressure.

The pressure-intensifying arrangement also provides the means for applying a pressure measuring device to the bulkhead to determine the pressure of the petroleum jelly during the compression operation. Figure 3 shows the device in operation. This measurement of pressure may also be repeated at any time without loss of pressure or petroleum jelly.

Examination of Figure 2 shows that a lead seal is employed in addition to the O-rings as an anti-diffusion seal against water vapour that may have passed through the O-ring system and tests have shown that the lead seal alone (i.e. without any preceeding O-rings) will not only operate as an anti-diffusion seal but also seal a housing against the full sea pressure in excess of 4 tons per square inch (630 kilogrammes per square centimetre). It can therefore be regarded as an additional safeguard in the extremely unlikely case of failure of the whole pressurised O-ring system.

The cable entry gland through the bulkhead is formed by a castellated stem machined integral with the bulkhead, through which passes a small diameter polyethylene insulated cable, the cable forming short tails on each side of the bulkhead. A polyethylene moulding is formed on the cable at the outer end of the stem which unites homogeneously with the polyethylene of the cable and also extends over the castellated portion of the stem. The contraction of the moulding on the stem, which is enhanced by the external water pressure, will provide a seal against the entry of water, but as an additional safeguard the stem is processed before moulding to ensure an effective bond between the polyethylene and the metal of the stem. The bore of the stem is threaded to form circumferential serrations into which the softened polyethylene of the cable is forced during the moulding operation. This provides an effective keying that prevents extrusion of the cable through the bulkhead, even with hydraulic pressure in excess of 5 tons per square inch (787 kilogrammes per square centimetre). This type of seal was developed by the British Post Office and is used on all their deep water submerged repeaters.

All glands are examined by X-rays to check for voids or foreign inclusions and are also subjected to a water pressure test at 5 tons per square inch (787 kilogrammes per square centimetre) for a period of 28 days.

The cable tail on the high pressure side of the bulkhead is provided with a braided outer conductor which is connected to the bulkhead via a perforated metal cup. Completely enclosing the moulded cable gland and the outer conductor cup is a moulded synthetic rubber bell that is filled with a viscous insulating fluid. Water, in the presence of which electrolytic corrosion might occur, is thus prevented from contacting the junction of dissimilar metals formed by the outer conductor cup and the bulkhead. When subjected to hydrostatic pressure the bell will collapse slightly until the pressure in the insulating fluid is comparable to that of the surrounding water. The cable tail on the low pressure side of the bulkhead is jointed to a corresponding tail from the repeater capsule which is contained within the pressure housing. The four turns of small diameter cable within the Jointing Chamber which are formed after jointing the tails from the repeater and the sea-cable not only allows for jointing to be carried out beyond the end of the

Jointing Chamber but also prevents any pull being transmitted to the bulkhead gland.

CORROSION PROTECTION

In order to reduce the risk of corrosion the whole of the outside of the housing is protected with a coating of sprayed zinc followed by three coats of vinyl paint. The inside of the Jointing Chamber and the End Cap and all parts of the cable anchorage are zinc oated by the Sherardizing process. The braided outer conductor on the small diameter connecting cable is protected with a coating of polyethylene based compound followed by lappings of polyethylene and PVC tapes.

No protection is applied to the bulkheads, pistons and inside faces of the casing. However, in spite of this lack of protection on these latter items experience has shown that the amount of corrosion that occurs is of such small magnitude as to render any anti-corrosion measures such as the fitting of sacrificial zinc anodes, unnecessary. Nor has any significant amount of corrosive attack been noticed on any of the zinc coated items.

The degree of corrosion encountered in service is illustrated in Figure 4. This shows a bulkhead (of earlier design) removed from a housing that had been laid in the Mediterranean at a depth of 600 fathoms (1100 metres) and recovered after $6\frac{1}{2}$ years in service; the housing was then stored, untouched, in Italy for a further $3\frac{1}{2}$ years.

As to be expected, Figure 4 shows that the surface of the bulkhead inwards from the outer edge of the outer O-ring groove had remained bright and clean. It is interesting to note however, that the bright, clean area also extended for a distance of approximately .020" (0.5 m.m.) beyond the outer edge of the outer O-ring groove. This is where deformation of the outer O-ring (under the petroleum jelly pressure) had extended the sealing into the gap between the bulkhead and the casing thus protecting the edge of the outer O-ring groove against incipient corrosion.

The amount of corrosion on the cylindrical surface of the bulkhead beyond the .020" (0.5m.m.) clear band can be judged by the fact that light "papering" with emery cloth removed the corrosive stains without obliterating the original fine machining marks on the steel.

The outer face of the bulkhead showed heavier corrosion though, even here, with the corrosion scraped away the original machining marks on the steel were still visible.

Figure 5 shows a section of that part of the casing that surrounded the bulkhead. Here again the degree of corrosion was such that it was easily removed with emery cloth without obliterating the original fine machining marks on the steel.

This evidence that shows what small amount of corrosion actually occurs in service is fully supported by a detailed examination that has been carried out on another housing that had been laid in the North Sea at a depth of 17 fathoms (31 metres) and recovered after approximately 10 years in service. The degree of corrosion on this housing was of the same order as that described above for the housing recovered from the Mediterranean.

Where LIGHTWEIGHT cables having an aluminium outer conductor are jointed to repeaters there could be some risk of electrolytic corrosion occurring because of the differences between metal electrode potentials. However, when pre-terminating the cable ends in the factory steps are taken to seal the termination against the subsequent entry of sea-water that would come into contact with the aluminium outer conductor. Furthermore, as an additional safeguard to afford protection in the event of a puncture occurring in the polyethylene sheath of the cable, heavy, sacrificial zinc anodes electrically connected to the repeater housing, are fitted round the cable terminations at the time of jointing the repeaters into the cable on shipboard.

CABLE AND REPEATER LAYING

Continuous lengths of cable to give the required repeater spacing are made up in the factory and armoured as necessary to afford protection in accordance with the requirements dictated by the type of sea bed, the depth of water and possible fishing activities as determined by a previously carried out survey of the route over which the cable is to be laid. The ends of the cable sections are also terminated to prepare them for subsequent connection to the repeaters.

The completed cable sections are loaded onto the cable-ship, in reverse to the subsequent laying order, and coiled-down in the ships tanks but with the ends of each section brought out on deck. Repeaters are accommodated in stacks on the decks between cable tanks and jointed into the cable as the loading operation proceeds. Thus the whole of the cable and repeaters on the ship (constituting, possibly, the whole of the submerged part of the system) is completely assembled before the ship leaves port.

Assuming that the size of the cable-ship, the depth of water, tidal conditions, etc. allow the ship to approach to within a reasonable distance (e.g. 0.5

mile) from the cable landing point at the start of the lay, the shore end of the cable will be floated ashore from the ship on a series of inflatable rubber floats; the cable being pulled from the shore by means of a winch or possibly a tractor.

In those cases where the cable-ship is unable to approach sufficiently close to the land to float the cable end ashore, the shore end cable will be laid out from the landing point by a smaller vessel, or barge, as a separate operation and the end of the cable buoyed-off in deeper water. Under these conditions the cable-ship would then pick-up the end of the shore-end cable, joint it to the end of the cable on shipboard and then proceed with the main part of the laying operation.

The total number of repeaters and the spacing between them has been pre-determined during the planning of the submarine cable system and is based on, among other considerations, the total length of cable between the terminal stations being known to a fairly high degree of accuracy. This calls, therefore, not only for very accurate navigation during the laying operation but also for very accurate control of the cable pay-out in relation to the distance covered by the ship.

In order to ensure that the cable closely follows the profile of the sea bed so as not to leave it in suspension at any point, it is necessary to pay-out a certain percentage of slack cable. The total amount of slack cable to be laid is a pre-determined figure and depends on the type of terrain to be covered. It is usually between 2 and 5 percent of the total distance between the landing points of the cable.

To enable the close control of cable pay-out to be realised it is necessary to have an accurate indication of the actual rate of progress of the ship in relation to the sea bed. This is achieved by navigation at the same time paying-out a "taut-wire". This is a high tensile steel wire which is anchored to the sea bed at the start of the lay and payed-out from the ship, as the cable is being laid, under sufficient tension to ensure that the wire is virtually straight. Varying the rate of the cable pay-out in relation to the "taut-wire" pay-out will of course, enable the percentage of slack cable being laid to be changed from time to time as required. When laying LIGHTWEIGHT cable in depths of, say 3 miles (4.9 kilometres) the catenary of cable suspended from the ship to the sea bed can be up to 20 miles (32 kilometres) long. Furthermore, it is possible that, say, three repeaters are also suspended in the catenary of cable. With the smaller 1.0" cables a parachute is attached to each of the repeaters to match their sinking rate to the cable but with 1.5" cables this has proved unnecessary.

It is obviously necessary to provide some braking means on the cable to prevent uncontrolled pay-out from the ship. This braking is simply achieved when laying un-repeatered cable by having a few turns of the cable round a large diameter braked drum. When repeaters are incorporated in the cable however, a difficulty arises in that the repeaters cannot be conveniently accommodated round the drum. This difficulty has been very successfully overcome by the use of the 5-sheave laying gear developed by the British Post Office. With this gear the cable is led over and under a series of five large braked sheaves to give the required traction on the cable and at the repeater positions a high tensile steel by-pass rope, which is attached to the cable before and after the repeater, takes the place of the cable through the 5-sheave gear whilst the repeater by-passes the sheaves.

Improved 'linear engines' for cable and repeater laying have since been developed by A.T.T. and the British Post Office. In the former case tractive effort is applied to the cable by caterpillar tracks and in the latter by a series of opposed rubber tyred wheels which 'grip' the cable. Both engines permit passage of the repeater in line with the cable, thus eliminating the need to man-handle the repeater and permitting higher laying speeds.

Throughout the laying operation all the repeaters (both in the ship and on the sea bed) are energised and transmission measurements carried out continuously from the ship to the shore and vice versa to check the performance of the system. The power to energise the repeaters is sent from the ship over the same cable used for the 'voice' transmission. Special filters in the repeaters separate the power from the transmission circuits.

It is essential that the gain of the repeaters, over the range of frequencies involved, matches the attenuation of the cable to a high degree of accuracy. Any mis-match is equalised at top frequency cable loss intervals of 500-600 dB dependent on the system involved. The equaliser networks are designed and made up on shipboard, based on the results of the transmission measurements on the laid cable and repeaters, and then inserted into pressure-resisting housings, that have already been jointed into the cable during the loading operation, following every twelfth or fifteenth repeater.

The design of the pressure-resisting housing for the equalisers is basically the same as that already described for the repeaters, the method of sealing the bulkhead into the casing being eminently suitable for an equaliser where the housing must be opened on shipboard for insertion of the networks and then finally sealed and tested prior to laying with the cable.

Upon completion of the main lay, which may have consisted of 2 or 3 separate laying operations depending on the capacity of the cable-ship and the length of the system, the ship will pick-up the buoyed-off end of a previously laid shore end cable, cut off the buffer cable remaining in the ships tank and then joint the main and shore end cables to complete the circuit between the shore terminal stations. Power to energise the repeaters will then be supplied over the cable from one or both of the terminal stations to effect communication.

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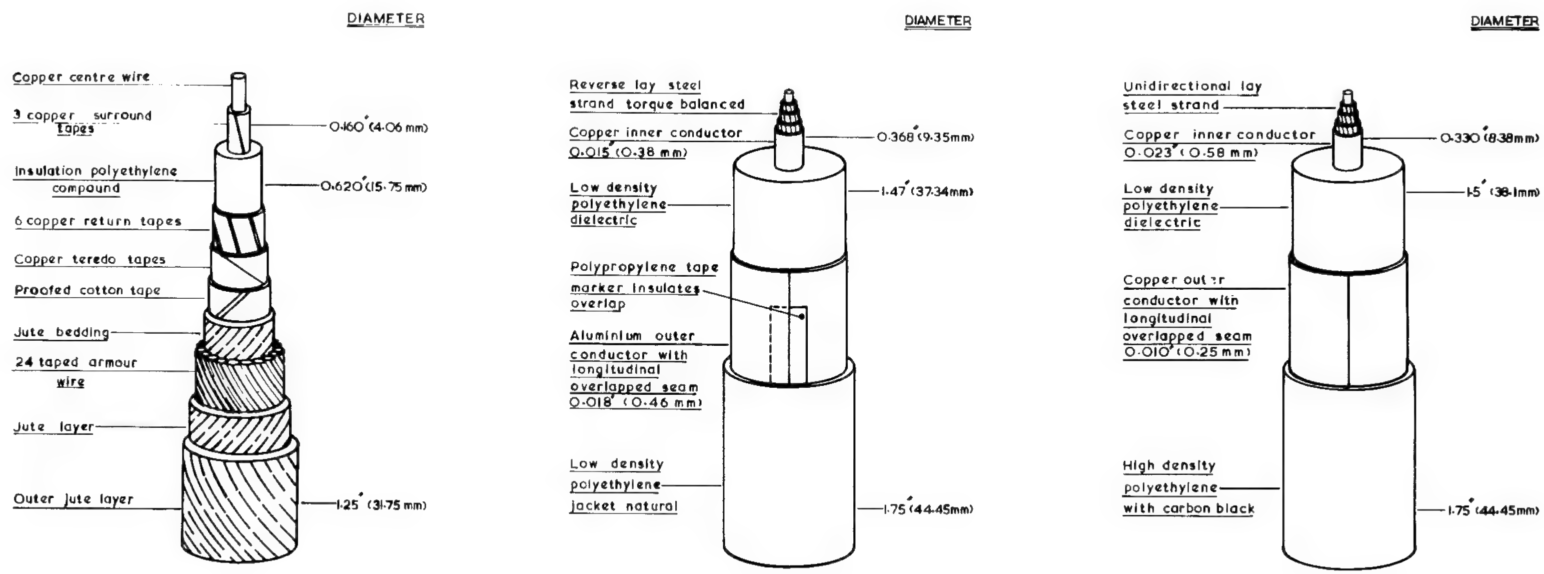
Colin F.G. Smith was born in England and educated at St. Mary's College, Southampton. Following national service in the R.A.F. he studied at the University of Southampton where he was employed for 5 years on development of equipment associated with a variety of aeronautical, civil, and mechanical engineering research projects. On joining the submarine cable factory of Standard Telephones and Cables Ltd., he was responsible for the design of automatic process control instrumentation and test equipment. Later he was engaged on development of new products and processes before being made Technical Manager responsible for cable, control and industrial engineering. More recently he has been appointed Manager, Cable Technology, of the Submerged Systems Division covering cable and hydrospace products. He is the holder of 14 patent applications and an Associate Member of the Institution of Electrical Engineers.

F.L. Jarvis was born in England in 1913. He was educated at the North Kent Technical College and later at the Leicester College of Technology. In 1935 he joined Standard Telephones and Cables Ltd., and was responsible for the mechanical design of transmission laboratory and factory test gear until 1945. He was then engaged on the mechanical design of waveguide components for micro-wave systems. Since 1949 he has been actively engaged in the mechanical design of all aspects of submerged repeaters and submerged equalisers.

DEEP-SEA SUBMARINE TELEPHONE CABLE



0.620" ARMOURED CABLE

1.47" LIGHTWEIGHT CABLE

1.50" ARMOURLESS CABLE

FIGURE 1.

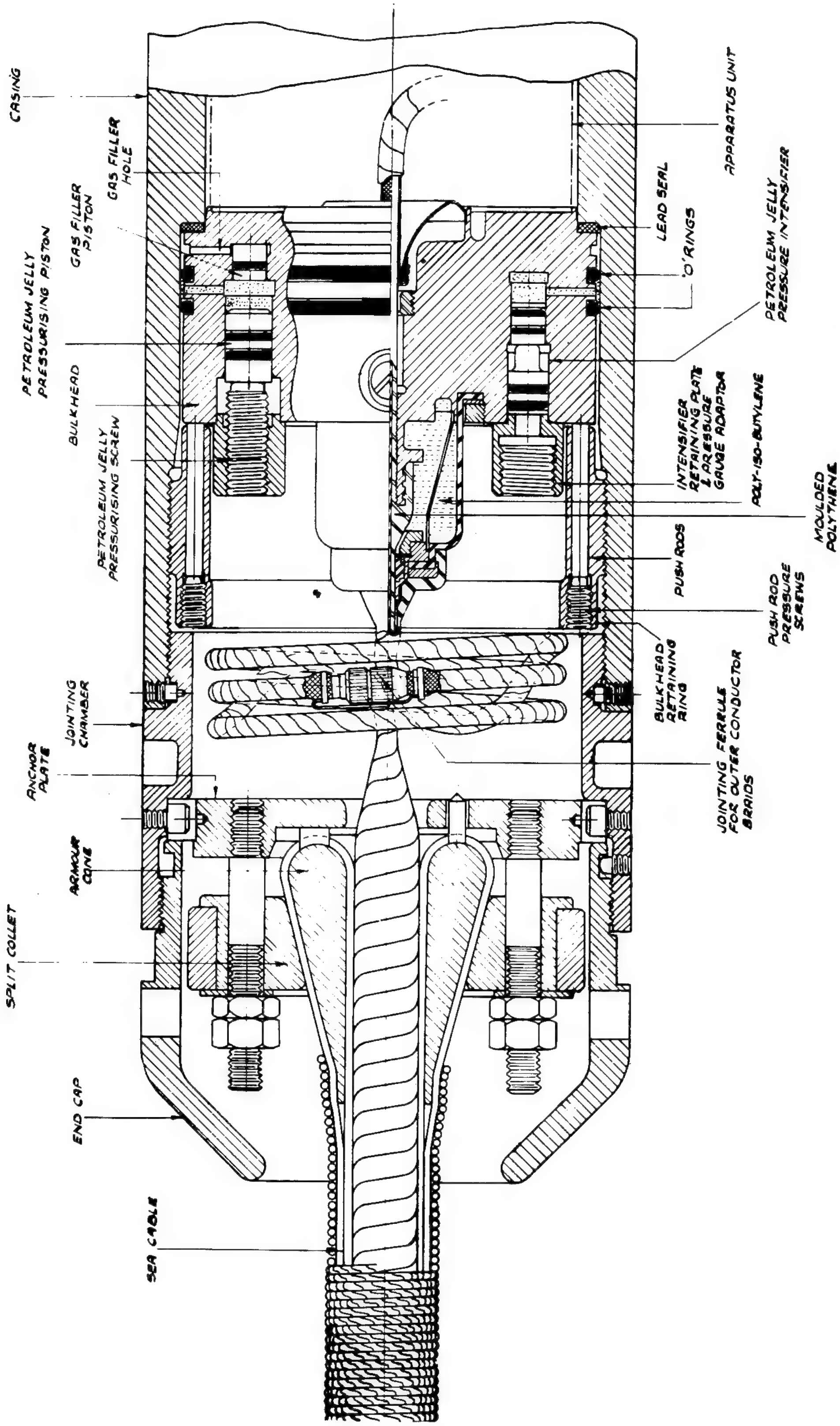


FIG.1 SECTIONAL VIEW OF ONE END OF PRESSURE HOUSING

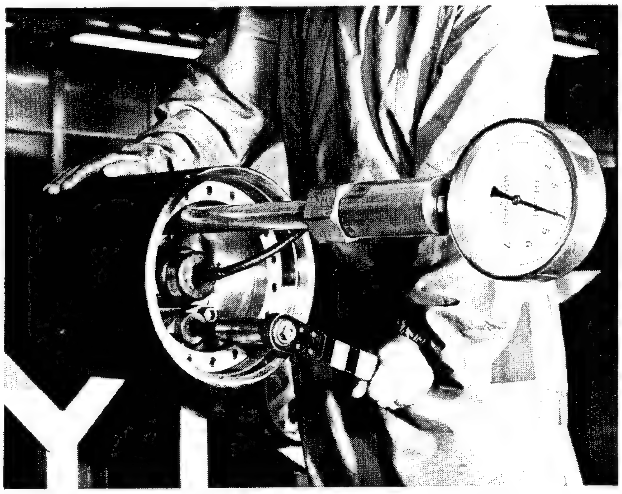


FIGURE 3 REPEATER BULKHEAD PRESSURE MEASUREMENT.

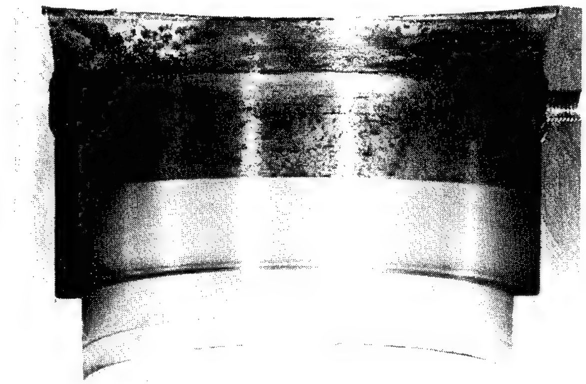


FIGURE 5 SECTION OF REPEATER CASING.

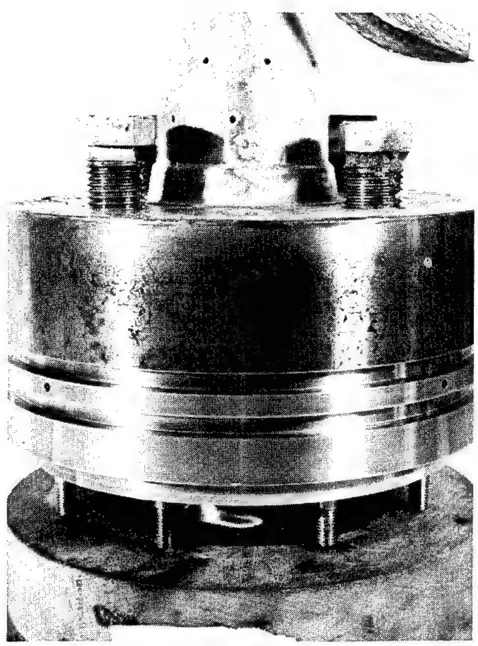


FIGURE 4 REPEATER BULKHEAD.

EXPERIENCE WITH NEW CONCEPTS IN DESIGN AND INSTALLATION OF SUBMARINE COMMUNICATION CABLES

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Southern New England Telephone Co.

J. V. McBride
Aqua-Tech

Summary

Extensive advancements in both cable design and installation techniques are resolving the serious reliability problems inherent with the situations in which Submarine Cables must be installed. Recent concerns about the disturbance of marine environments add further complications to the already complex problems involving Submarine Cable systems.

To provide essential service reliability, a Submarine Cable installation must satisfy the following major criteria:

1. The cable must be designed to endure continuous immersion for a service life of at least 30 to 50 years without serious transmission deterioration.

2. The tensile strength of the cable and the method of installation must provide ample safety factors so no damage is inflicted during installation.

3. In place, the Submarine Cable must be protected effectively against mechanical disturbance, and against exposure or bridging resulting from bottom erosion.

4. Both the method of installation and the cable in place must not disturb the marine Ecology seriously, nor interfere with the commercial gathering of marine harvests.

5. With service reliability as the primary requirement, installation and operational cost savings are also vital.

Traditionally, Submarine Cables have been designed with the highest quality materials for this hazardous service. The outer covering was usually one or two layers of helical wire armor. The primary function of the so-called armor was to provide supplementary tensile strength for deep-water laying. The armor wires also provided a limited degree of protection when caught by ship anchors and commercial fishing gear.

Over the past decade the Bell Laboratories and AT&T have made remarkable advancements in the design of "armorless" Ocean Communication Cables, and methods of installation, including plow embedment across the relatively high-risk areas of the Continental Shelves.

Starting in 1958, increasing quantities of unarmored power cables have been installed across intracoastal waterways. The polyethylene insulation and the impervious welded, corrugated copper sheath demonstrated excellent service reliability. Mechanical damage became the major remaining problem to be solved.

A special cable plow was designed to insert the cable into the bottom subsoil through a narrow incision to a safe depth. The incision created negligible ecological disturbance, and healed promptly providing the cable with the maximum protection afforded by a cover of essentially undisturbed bottom.

This method was considered unobjectionable by the Environmental Protection Agency in "high value water use areas". It was also acceptable to shell fishermen as means of installing cables across valuable commercial shellfish properties without objectionable disturbance.

In a delicate situation near the Long Island Sound shore of Connecticut, cables of the Southern New England Telephone Company crossing commercial shellfish areas were installed by the Aqua-Tech plow method to the satisfaction of all parties concerned. Traditional 12 to 101 pair wire-armored Submarine Cables were involved in the basic program. Two sections of the 2 pair Entrance Cable were also included.

As a trial installation, to test the reliability of the Aqua-Tech type of installation with other relatively small and physically weak buried type wire, the Brand-Rex Company supplied unfilled 3 pair Buried Distribution Wire which was terminated for periodic tests at the shore end. Two constructions were used, one with a

5 mil helical bronze shield, and the other with 4 mil copper/stainless-steel/copper laminated shield.

Utilities are naturally reluctant to put new concepts into service that may involve some risk, unless they have demonstrated a good service record under similar conditions for a number of years. However, cost factors are becoming so serious that the possibility of savings of the order of 50% of the typically expensive submarine crossing cost is stimulating consideration of improved materials and methods. Meanwhile, substantial accumulated experience with unarmored cables and new installation techniques in related fields is accelerating interest in these directions for underwater communication cable applications.

Introduction

Where communication cables must cross intracoastal waterways in the form of rivers, lakes, bays, estuaries, etc., they are usually important main route cables, warranting special investment. Since they will be exposed to unusual hazards peculiar to marine environment, they must be protected effectively to assure long, reliable service. Obviously, the cost of repairing a damaged submarine cable may be many times that of a land cable (buried or duct), and the service interruption may be days instead of hours.

Traditionally, it has been considered that an expensive super-cable with a rugged impervious sheath and one or two layers of heavy steel wire spiral armor was essential for this type of service. In all too many cases this extraordinary armor protection failed when a hazardous situation arose.

Dragging ship anchors, shellfish dredges, bottom-fishing gear, dredge spuds and channel dredging activity usually were more than a match for the best armored submarine cables when there was contact and a test of strength. This led to intensive research and redesign of both cable construction and installation methods for ocean communication cables which had suffered from these mechanical hazards.

However, standard practice for communication cables across intracoastal waterways is still, "Wire armored submarine cable laid loosely on the bottom". In some cases submarine cables were laid in a dredged trench to obtain additional clearance from ship propellors and channel-dredging operations. However, unless expensive, firm backfill is used, the soft, natural backfill offers little protection against penetrating mechanical hazards.

Developments

During the reconstruction in Europe following WW II, the "hardening" of cables in land and in waterway crossings by deep burial became a standard practice. Since the dredging of deep trenches was very expensive, Harmstorf of Hamburg developed special plow-like devices with which submarine cables could be buried at great depths to achieve any desired degree of protection. A number of installations of this type have been made in the USA, including multi-duct structures.

In some situations utilities have considered that submarine cables with wire armor had too great exposure to mechanical damage when they were just laid loosely on the bottom of a busy waterway. Consequently, there developed a practice of having a diver hand-jet a cable into the subaqueous bottom by undercutting it with a water jet. The stiffness of the cable usually limited the practical depth of burial by this method. Furthermore, the natural backfill that accumulated above the cable was soft and offered little, if any, mechanical protection to the cable.

Greater subaqueous burial depths have been achieved by the use of jet-blasting, using the output of several large pumps to excavate hydraulically an unstable trench into which the cable was laid. However, with this method also, the soft, natural backfill afforded very limited mechanical protection for the cable.

Meanwhile, great progress was being made through the 1950s and 1960s with the plow burial of communication cables in rural areas. Basically armorless cables plowed in only several feet into the ground through a narrow slit were effectively protected by the cover of several feet of essentially undisturbed soil. It was felt that this method might be adapted to utilize armorless submarine cables and provide them with ample protection for a great many intracoastal waterway crossings.

Aqua-Tech designed and built a portable unit to the specifications of a power utility to embed cables up to 5.5" O.D. at least 30" into penetrable submarine subsoil. A number of miles of armorless cables up to 25 kv rating were successfully installed. Even URD cables, designed for land plows, became reliable submarine cables when installed by this method. Increasing savings in installed cost were achieved through the use of armorless types of cables and refinements

in installation techniques and equipment.

Environmental Considerations

As with the land cable plowing method, the underwater cable is "embedded" into the subsoil with negligible disturbance by the Aqua-Tech method. This provides the cable with effective mechanical protection and avoids the substantial disturbance of the environment created by trenching or jet blasting. Environmental Protection authorities consider the Aqua-Tech method as being unobjectionable, even in critical areas, defined as "high value water use areas". Consequently, this method has two major advantages in creating negligible disturbance of the environment while providing essential mechanical protection for the cable. In addition, it usually achieves substantial cost savings as compared to convential installation methods.

Experience

Submarine cable placing methods employed by the Southern New England Telephone Company to this time have been most frequently based on a system of laying the cable on the bottom and sinking it in to some extent with water jet-blasting equipment. On occasion a dragline or dredge has been employed to provide a trench prior to the cable placing operation. Depending upon the nature of the job, cable is placed by boat, drawn over the crossing on floats, or merely pulled across the bottom with a winch line.

These methods provide little or no mechanical protection for the cable after it is placed. Cable placed exposed on the bottom is vulnerable to damage and in time the armor deteriorates, leaving the cable completely unprotected. Excavating prior to placement requires a trench with sides having a slope of up to 3 or 4 to 1 to assure stability until the cable is laid in the trench. This means that over a half cubic yard of material must be removed for every linear foot of trench thirty inches deep. Hand-jetting the cable into the bottom requires nearly the same excavation to effectively place the cable to the same depth below the existing bottom. An effective, firm backfill is rarely used because the cost is prohibitive. Usually natural sources provide the backfill--thus for several years the material settling back into the depression is of a lighter, more silty consistancy than the undisturbed areas. Heavy objects such as anchors will easily penetrate this inadequate, soft cover protection quite deeply, increasing the probability of damage to the cable or armor. The Southern New England Telephone Co. had a project to place about fifteen thousand feet of cable and service wire to and among a group of offshore islands where the maintenance of the existing cable and wire had reached an intolerable stage. The islands were in an area containing shellfish beds owned by the Long Island Oyster Farms, Inc., of New York. While the area contains some oysters, it is planned for future use as clam beds. The area is also used as an occasional anchorage for small recreational craft.

The situation presented two major problems. The cable had to be buried and protected effectively from anchors and from commercial clam dredges which penetrate the bottom to a depth of six to twelve inches when harvesting clams. Also, any appreciable amount of silt raised by the embedment process would have a detremental effect on the existing oysters. The right-of-way agreement across approximately two miles of the Long Island Oyster Farms property was contingent upon their approval of the method used. An additional problem was that the depth of water at some stages of the tide precluded the use of anything but very shallow draft equipment. The process used to satisfy all requirements, and coincidentally the economic one too, was a technique involving a sub-aqueous plow device developed by Aqua-Tech of Lebanon, Conn.

Special design of the plow permits easy movement through the soil while it embeds the cable thirty inches deep in a six inch wide incision. Negligible turbidity is created and the surrounding soil remains virtually undisturbed and retains its original compaction, thus providing maximum mechanical protection for the cable.

Because of the lead time requirements on ordering cable, an order for armored cable for this project was placed prior to the time we became aware of this unique embedment process. Had the process been familiar to us, and adequate field presurvey time provided, about 60% of the cable used could have been duct type, armorless. In addition to substantially reducing the material costs ($15,500) the considerable cost and problems associated with the transportation of the very large and heavy submarine cable reels could have been largely eliminated. For instance, one of the cable reels was fourteen feet long, eight feet in diameter, and weighed 22 tons. A subsequent pre-survey of the bottom conditions determined these areas of the cable routes that permitted embedment. An inspection of the selected route by a diver was also found to be advantageous. The equipment used in the embedment method consisted of a shallow draft barge

which carried the cable and pulled the plow, a winch which moved the barge when plowing, a twin screw flattop work boat that draws only a few inches of water, and associated equipment.

Embedment was accomplished by running the winch line along the cable route to an anchor point, then winching the barge to the anchor. The cable reel mounted on the barge feeds the cable directly to the plow towed behind the barge. Tension on the plow is carefully monitored so that subterranean obstructions interfering with the embedment are quickly detected and the operation can be halted, permitting correction of the condition before material or equipment damage occurs. During the plowing operation, a diver in telephone communications with the barge, constantly circles the plow to spot and clear obstructions encountered on the bottom, or report any unusual conditions.

The route of the barge can be carefully and accurately controlled because of the anchor technique. This permits cable to placed with a high degree of precision along a pre-determined route and provides for a situation that should produce accurate as-built records.

The design of the plow permits embedment in the beach above the waterline, eliminating the costly excavation in the tidal splash area and requiring only that trenching be done in the dry ground.

Increasing concern of individuals and agencies about the effects of utilities construction on the environment dictates that we examine our practices in this regard. This embedment process would appear to satisfy such concern, as it has been considered unobjectionable by environmental authorities as well as being economically advantageous in many types of submarine cable construction. A continuing exploration of new concepts and processes that minimize the impact of our operations upon our surroundings is essential if we are to be prepared to cope with these problems as they arise.. and do it within the economic realities of the business world.

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TOWED CABLE

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ABSTRACT

This paper describes, out of all towed cables that play an important role in oceanic development, a cable using fiber rope which gives it a high tensile strength and flexibility and makes adjustment of its specific gravity possible.

The cable can be kept horizontal and that therefore the posture of the sonar can stay horizontal too.

1. INTRODUCTION

Recently oceanic development has been making spectacular progress for the positive utilization of marine resources, and along with it, increasing importance is attached to the equipment for oceanic investigations. In particular, a variety of devices have been developed for a cable for towing measuring instruments undersea by ship, etc. for surveying purposes.

For example, a cable used for a sonar device sunk in the sea which makes precise detection by freely changing its depth and reducing the effect of refraction arising from the undersea temperature difference is fitted with fins to prevent the erroneous function of the sonar due to the turbulence while the cable is being towed. And a cable for towing measuring instruments by airplane or helicopter which survey mineral deposits or veins by the use of change in magnetism has an outer covering of titanium braiding to make the cable non-magnetic and eliminate noises. As for a towed multiple hydrophone cable which is intended for use as a light weight small-size undersea sonar, the part of it from the middle down has a different specific gravity from the front half so that the end portion of the cable can be kept horizontal and that therefore the posture of the sonar can stay horizontal too.

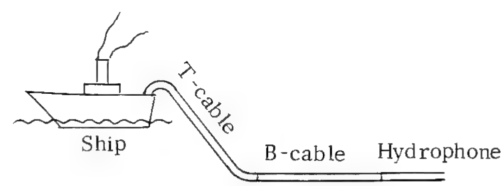
The towed cables, which are multifarious in kind and type as explained above, are all required to have the ease of handling, a high tensile strength and a good flexibility. In this report, the towed multiple hydrophone cable is taken up as an example of design and manufacture and its construction, characteristics and performance are introduced.

2. REQUIREMENT

The towed multiple hydrophone system, as illustrated in Fig. 1, is composed of a hydrophone, a B-cable and a T-cable which are jointed one after another, and the whole system is towed by ship. The T-cable has a specific gravity of 2 and sinks in the sea so as to make the hydrophone work more effectively than otherwise. The B-cable, having a specific gravity of 1 to keep the hydrophone in fit and appropriate posture, is so designed as to be capable of floating at any given undersea level.

Fig. 1

Towed Multiple Hydrophone System



The requirements of the cable are as follows: (Table 1):

Table 1 Requirement

T-cable	
Specific gravity:	2 or more
Tensile strength:	2.5 tons or more
Water pressure resistance:	50 kg/cm^2 or more
Bending strength:	200 or more
B-cable	
Specific gravity:	0.98 – 1.03
Tensile strength:	1 ton or more

Water pressure resistance: 50 kg/cm^2

Specific gravity change: 25% or under

Bending strength: 200 or more

Besides, as shown in Table 1, the cables are designed to have a bending strength of withstanding 200 bendings or over; which is a considerably severe requirement.

On the other hand, the electrical properties are:

Conductor resistance: 170 MΩ/km or under/signal wire 19 pairs

Insulation resistance: 200 MΩ ·km or over

Dielectric strength: AC 500 V/one minute

Crosstalk: 80 dB or over

The most important of all is that the T-cable and the B-cable should be not a jointed but a continuous length.

3. DESIGN, MANUFACTURE AND EVALUATION

We made a cable design on the foregoing conditions. What we first considered was a cable having a construction shown in Fig. 2. It was to be so constructed that a tension member was inserted in the center and that the part was surrounded by signal wires; the adjustment of the specific gravity of the B-cable was to be made by means of a polyethylene pipe. The evaluation of the cable is given in Table 2. As, however, the PE pipe for specific gravity adjustment proved a weak point, our first design had to be revised. On the basis of this experience we designed, as a second, a cable as shown in Fig. 3-5 and evaluated it, with the result given in Table 3.

Fig. 2 Construction of Cable

Type A

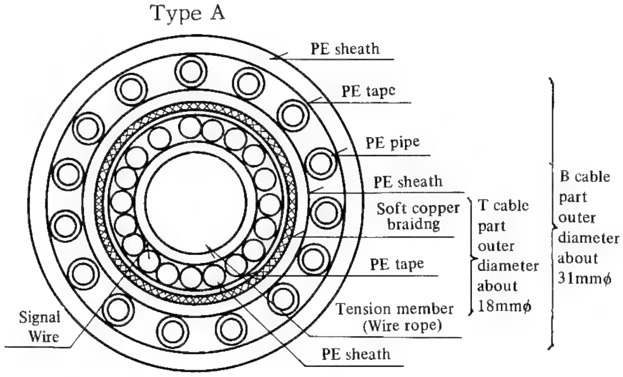


Table 2

1. Specific gravity adjustment is done by PE pipe.
2. PE pipe is crashed under water pressure of 50kg or under.
3. T cable and B cable parts have different outer diameters.

Fig. 3 Construction of Cable

Type B

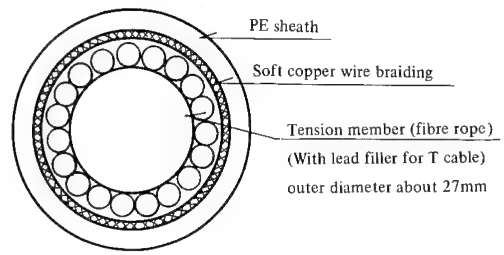


Fig. 4 Construction of Cable

Type C

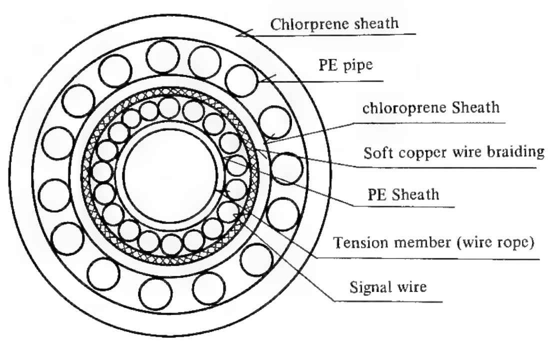


Fig. 5 Construction of Cable

Type D

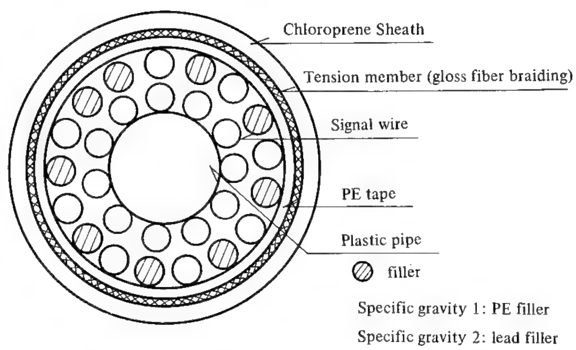


Table 3

Type b

1. Specific gravity adjustment is done by means of compactness of braiding. (very difficult)

2. T-cable part has lead filler inserted in the center. (very difficult)

3. Tape is used for fiber and acts as tension member.

4. Outer diameter: about 27

Type c

1. Almost the same construction as a (in tension member, specific gravity adjustment and outer diameter).

2. Chloroprene is used for sheathing material (which means better flexibility).

3. Outer diameter: T-cable part about 19
   B-cable part about 31

Type d

1. Glass fiber braiding is used for tension member.

2. Specific gravity adjustment is done by PE or lead filler.

3. Central pipe is unsuitable in point of water pressure resistance.

4. Outer diameter: about 22

Table 4

	Glass fibre	Nylon	Steel wire
Tensile strength (kg/mm^2)	130 - 300	40 - 90	12 5
Specific gravity	2.52	1.14	7.8
Elongation (%)	3 - 4	14 - 25	

Fig. 6 Construction of Cable

Type E

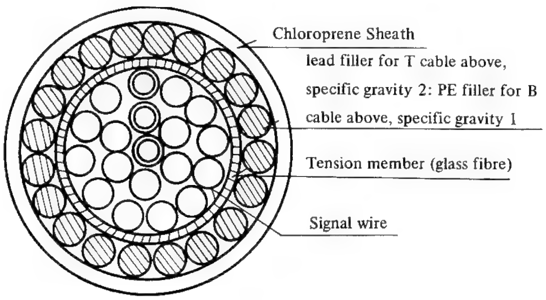
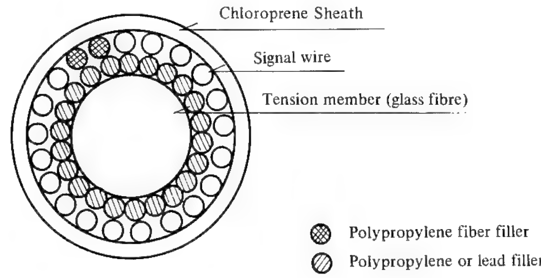


Fig. 7 Construction of Cable

Type F



On examining methods for specific gravity adjustment we found that (b) was hard to control by means of braiding, that (c), like (a), wanted in PE pipe strength and that (d) lacked in the strength of center PE pipe, that is, the cable did not pass muster in the pre-study stage and so failed to go into the stage of trial manufacture. But at this stage, two noteworthy concepts came up: 1) a fiber rope was adopted despite the fact that iron, stainless steel and other metals were chiefly used for the conventional tension member. The characteristics of the fiber rope are as per Table 4. 2) Use of a lead filler for the purpose of adjusting the specific gravity of the cable. This was only feasible by the use of the above fiber rope, and it served rather as a sinker for the light cable (specific gravity ≒ 1).

As last ones, we designed (e) and (f). Fig. 6-7 and Table 5 show cable construction and our evaluation respectively. As a result, we realized cables of the same diameter in which the portions from the middle down had a different specific gravity, and made a final check of their properties in various tests.

4. RESULT OF TEST ON FINAL DESIGN

The following 4 test items were made:

1. Bending test

2. Water pressure specific gravity test

3. Tensile strength test

4. Electrical test

Methods of 1 to 3 were as per Fig. 8-10. In (1) bending test, there was found a difference between (e) and (f); so that the remaining tests (2, 3 and 4) were carried out only on (f) which proved better in the bending test.

Result of bending test:

Kind of cable		Bendings until one conductor was broken
Type (e) cable	T-cable	360
	B-cable	1100
Type (f) cable	T-cable	150
	B-cable	540

Fig. 8 Bending test

The samples were tested by bending tester as follows:

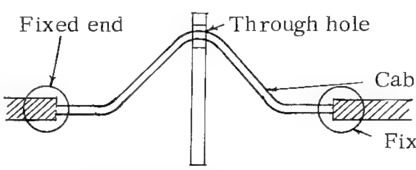


Fig. 9 Water pressure-specific gravity test

Amount of air pressed out was measured at the measuring unit.

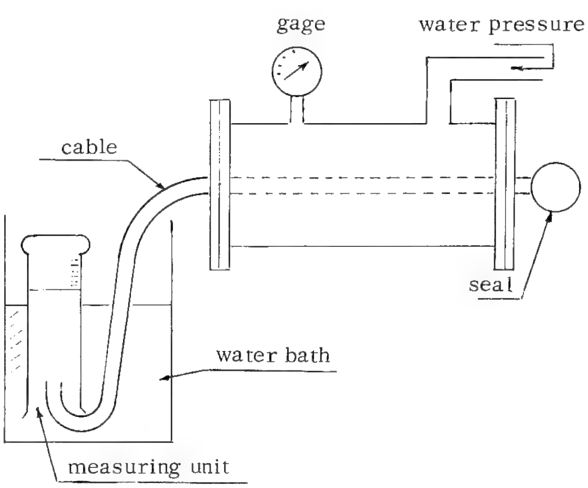
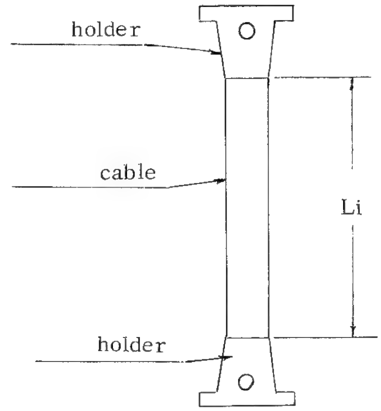


Fig. 10 Tensile strength test

When holder was fitted to the sample and test machine was given a load, li was measured.



Result of test of specific gravity versus water pressure:

As shown in Fig. 11-14.

Only the result (e) of tensile strength test

Load (kg)	Length li	Elongation
200	3100	
400	311	
600	3,115	
800	3,125	
1,000	3,130	0.97 %
2,000	3,200	
2,500	3,220	3.87 %

Result of electrical test

Conductor resistance:	Max. 132 Ω/km
Insulation resistance:	Min. 400 KMΩ /km
Dielectric strength:	500 V/min
Crosstalk (worst):	80 dB/600 m (at 6 KHz)

Fig. 11 Type (e) T-cable part

Specific gravity 2.16

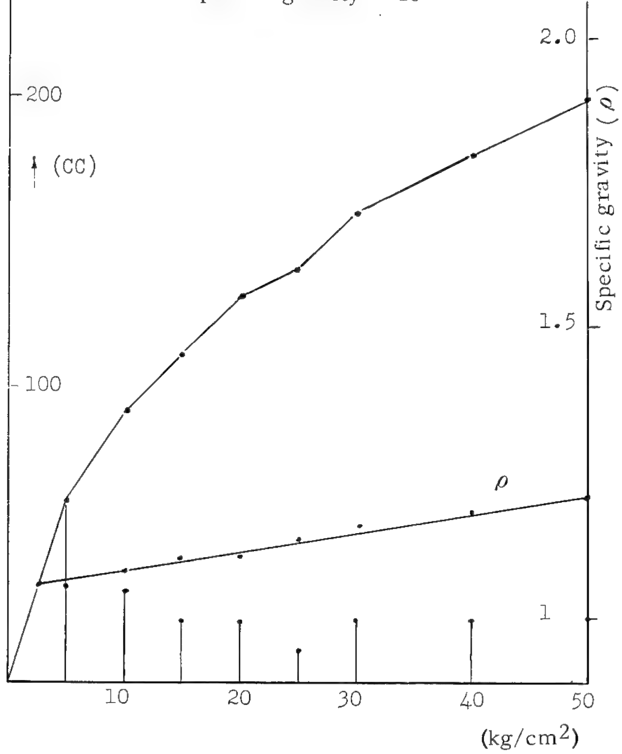


Fig. 13 Type (f) T-cable part

Specific gravity 2.0

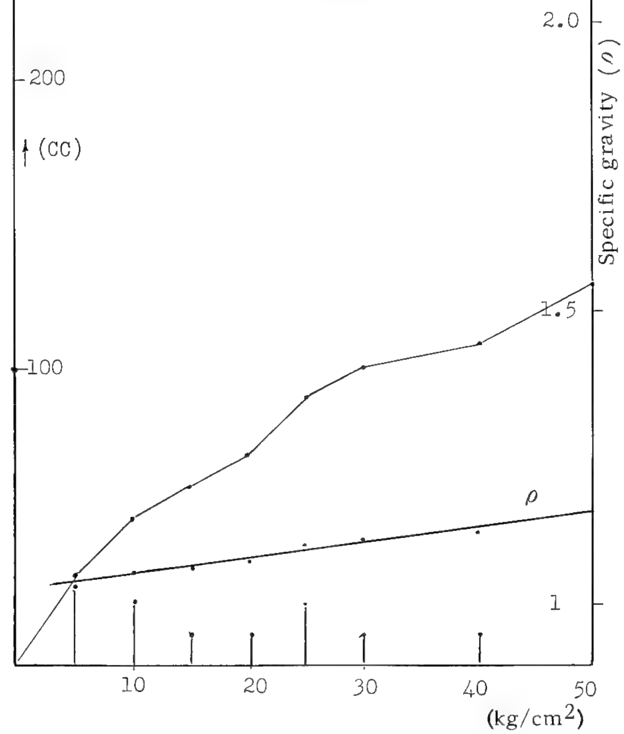


Fig. 12 Type (e) B-cable part

Specific gravity 0.98

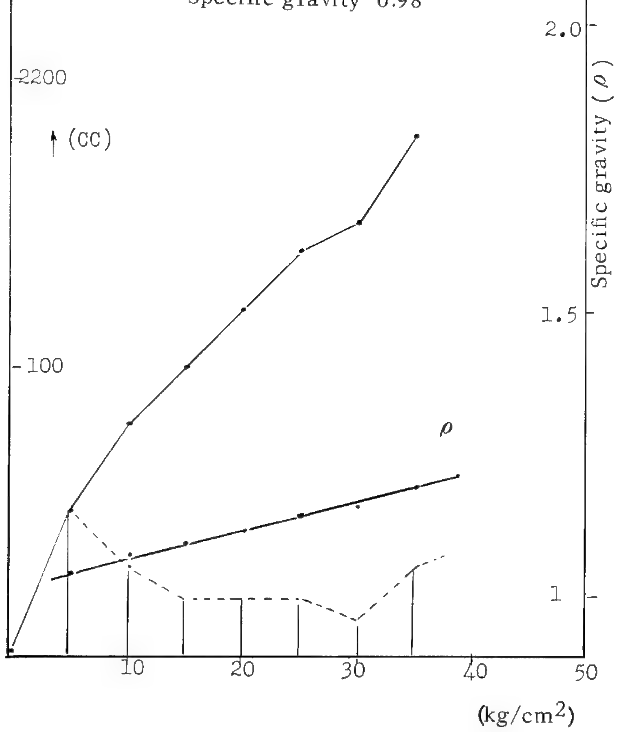
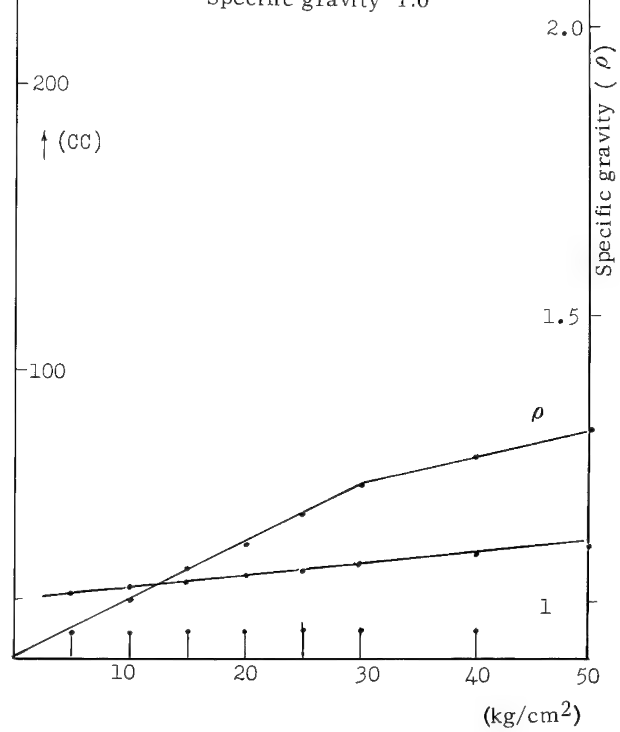


Fig. 14 Type (f) B-cable part

Specific gravity 1.0



5. CONCLUSION

From the results of our various studies we concluded that Type (e) was the best of all. Of course, it filled the requirements of 2. The technical achievements we had in our test are as follows:

1. It has now become possible to manufacture a cable of different specific gravity values in one continuous length.

2. We can now produce a high tensile-strength and flexible cable by the use of glass fiber that is given special processing.

3. Specific gravity adjustment can be made comparatively easily through the use of special filler.

As mentioned in the beginning of this report, the towed cable has a number of applications and is expected to make further development. We believe the technique introduced here will play an important role in fishing nets, suspension type deep-sea measuring instruments, and other devices for oceanic development.

6. REFERENCE

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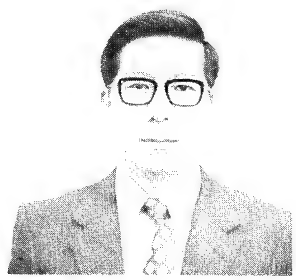

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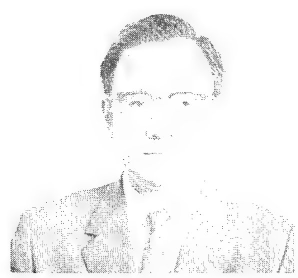

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WHAT FUTURE IS THERE FOR WIRE AND CABLE IN ARMY FIELD COMMUNICATIONS?

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ABSTRACT - Current and future Army uses and inventories of wire, cable, and construction facilities are outlined in an attempt to answer the question posed by the title. Continued cooperation between industry and the Army is sought in the development, refinement, and production of new wire, cable, and construction facilities to meet changing requirements.

I. INTRODUCTORY REMARKS

In this unclassified paper, an attempt is made to answer the question posed by the title as to the future of Wire and Cable in Army field communications. Or to ask the question more bluntly, who in the Army needs wire and cable when almost everyone has a radio?

Within the Army and even among the authors of this paper, there are wide differences of opinion as to how much wire and cable will be used, if at all, as a means of communication in future Army field operations. The direction such uses may take in the future is also a subject of much conjecture.

A brief review of past and present Army uses of communications wire and cable is followed by a discussion of the pros and cons, adequacies and inadequacies, of wire as a present and future means of communication in the Army. The projections resulting from an assessment of this discussion are the authors' attempt to answer the question posed in the title of this paper and indicate ways in which the wire and cable industry, in cooperation with the Army, may further the development, refinement, and production of new wire and cable, and the necessary construction means for their installation, maintenance, and recovery.

Discussion herein deals primarily with outside plant communications uses in overseas military theaters of operation. No consideration is given to US post, camp, or station uses, to internal wiring inside of equipment or shelters, nor to power cabling inside or out, although admittedly the size, weight, cost, and immobility of outside power cabling are problems in field communications.

II. BACKGROUND

Army communications have almost completed a full revolution, from wireless through wire to wireless again. Use in the early 1800's of flashing lights, flags, smoke signals, heliograph, and hand signals in the visible spectrum gradually gave way to use of telegraph and telephone over wire and cables in the late 1800's and early 1900's. The introduction of single-channel radio telegraph in World War I evolved into multichannel wire systems in World War II. Extensive use was made of open-wire, field cable, field wire, and fixed-plant commercial lead-covered cable. Line of sight multichannel radio relay, introduced at the close of World War II, was exploited in the Korean conflict to further reduce the use of field wire, field cable, long-haul cable, and open-wire. The advent of tropospheric scatter multichannel radio systems in the latter stages of the Korean conflict has been augmented by the use of satellite relay in Southeast Asia resulting in increased communication capabilities without a corresponding increase in the amount of wire and cable. Despite all of these new uses of the electromagnetic spectrum, the Army has continued to need large quantities of wire and cable in its active operations.

Now let us examine the present day Army communications concept, Army usage of wire, and the relative advantages of wire and radio. This examination should help us to highlight those areas in wire and cable communications which should be improved if the Army is to make optimum use of wire and cable in future operations.

III. CURRENT ARMY COMMUNICATIONS USE OF WIRE AND CABLE

Our present day communications concepts envision the use of a mix of wire and radio facilities. Generally, the more maneuverable elements of squad, platoon, company, and battalion size in the forward combat echelons depend almost entirely on single-channel net radios for voice communications. These are provided primarily by manpack and vehicular, frequency-modulated radios with some single sideband radios. Limited use is made of field phones, single pair field wire, and small switchboards for perimeter defense, command post, inter-echelon, and fire control communications during static situations over distances of a few yards to five miles or so.

In the less maneuverable elements of brigade, division, corps, and field Army, that is the higher combat echelons in the rear of the combat zone, much less dependence is placed on single-channel net radio. In these echelons, the long-haul and

trunking links between command posts and headquarters are provided by multichannel radio relay systems having terminals mounted in shelters and transported by trucks. These systems currently provide thirty-mile line of sight links and hundred-mile tropospheric scatter links. Limited amounts of frequency-modulated radios and radio teletypewriters are also used. Local interconnections between multichannel radio sites and multiplexer shelters, links up to about five miles long, are provided by twin-coaxial cable which is rapidly replacing spiral-four cable, and may be provided, in the future, by multichannel radio links. Twin-coax is also planned for use as an alternate for multichannel radio links when required by the situation and when time for its installation is available. In these higher combat echelons large amounts of 26-pair field cable are used to interconnect multiplexer shelters, patching panels,switchboards, and local telephone subscribers over distances of a few hundred feet.Single-pair field wire is widely used in the higher combat echelons for telephone loops of a mile or so in length extending from 26-pair cable terminals and direct from switchboards. With the limited introduction of automatic electronic switching at these echelons, a need has arisen for a two-pair field wire, generally referred to as a four-wire field wire, for use as loops to four-wire field phones. The increased use of four-wire trunking and loops requires more 26-pair cable or larger cables as we shall discuss later.

In the supporting and logistical elements above field Army level, that is in the communications zone to the rear of the combat zone, communications are provided by a variable mix of rehabilitated indigenous multichannel radio and cable systems, Army-installed commercial-type fixed radio and cable plant, and transportable wire and radio systems similar to those just described for the combat zone. Commercial plastic insulated cable has been widely used for buried and aerial construction in base camps and large headquarters areas. Open wire usage is practically nonexistent except possibly for rehabilitation of existing indigenous systems.

We have mentioned Army wire and cable facilities such as single-pair and four-wire field wire, 26-pair cable, spiral-four cable, and twin-coaxial cable. Appendix I includes descriptive and technical information on these standard Army items. No attempt is made to give such information on the wide variety of well known commercial items used by the Army in the communications zone.

Much of our field wire is laid on the ground or in roadside ditches, especially in forward areas where time does not permit a more secure type of construction. In our rear combat areas, wire and cable is laid on the ground initially but almost immediately is placed on overhead supports, or preferrably buried so as to survive the off-road vehicular traffic in most areas.

We use relatively simple construction tools, reeling units, test sets, plows, line trucks, and earth borers for the installation and maintenance of our wire and cable lines (see Appendix II). Some of these construction facilities are obsolescent and are being replaced with more up-to-date versions of commercial equipment such as: earth augers, line construction trucks and new types of ditching machines.

The current trend in Army communications is to place more reliance on radio while wire use is diminishing quite rapidly. Less field wire is used in all tactical echelons, especially in forward areas. Use of long-haul multichannel cable is almost nonexistent. Use of multi-pair cable has increased somewhat for local distribution and inter-shelter cabling in headquarters, command posts, and communication center complexes.

IV. POSSIBLE FUTURE ARMY COMMUNICATIONS

Will the foregoing trends of increasing use of radio and decreasing use of wire continue into the future? Will there be further reductions in the use of field wire in forward areas, elimination of long-haul cable in rear areas, and reduction in use of twin-coax and multi-pair cable in rear areas? To answer these questions, we must look at the reasons for these trends or at why radio is increasingly favored over wire and cable.

Many types of radio can be used while being carried by men and vehicles; most field radios can be quickly and easily set up, operated, removed from service, and reinstalled repeatedly; radio can span inaccessible or enemy held terrain; its radio paths are not subject to disruption by friendly and enemy vehicular traffic or weapons fire although its radio terminals are likely enemy targets; and radios contain relatively small amounts of scarce metallic resources.

On the other hand, present radios require continuous large amounts of prime power or an uninterrupted supply of batteries; our radio signals can be easily intercepted by the enemy and information about our plans and operations can be obtained from clear and at times from encrypted transmissions; our radio receivers are vulnerable to jamming by the enemy or unintentional interference by our own transmitters by direction finding and as a result may be able to destroy our transmitters by fire from his weapons; the radio propagation paths frequently vary unpredictably over wide limits of noise and transmission loss; line of sight radio paths may be difficult to obtain or may become obstructed; usable radio-frequency spectrum space, as we presently know it, is becoming increasingly difficult to obtain; present radio systems require highly trained maintenance personnel and complex repair facilities; and finally the radio transmitters, receivers, terminals, repeaters, and antenna systems are heavy, bulky, and costly items particularly for the longer-haul multichannel systems.

Many of the foregoing disadvantages of radio are circumvented or diminished by use of wire and cable. For example: enemy interception, jamming, destruction, and location of wire and cable is much more difficult; wire transmission paths are relatively stable and predictable; scarce frequency spectrum space is not required although each cable has finite limits at present; our own wire communications generally do not unintentionally interfere with each other; line of sight paths are unnecessary; and less prime power is usually required.

However, existing wire and cable is bulky, heavy, costly, difficult to transport and store, and time consuming to install. Although it is recoverable and reusable, time normally does not permit recovering in large quantities. It is also subject to destruction by friendly vehicular traffic, by sabotage and by enemy shell fire unless deeply buried; it is difficult to trouble-shoot and repair in the field; and large quantities of scarce raw materials are used.

Wire and cable facilities have provided us with high-quality reliable communications at all levels within the Army in the field and we need only look at the communications structure created by our forces in Vietnam to verify the reliance placed on wire and cable in the routine and emergency conduct of our daily business. However, as national objectives, strategies, and programs change and as the rapid pace of technological advance accelerates, it is only reasonable to expect that the means available for satisfying the ever increasing Army user communications need will come under even closer scrutiny while we continue to look for the best answers at the lowest system price tag.

Our present well-publicized strategies call for reliance in any future hostilities on aerial supply and resupply systems designed to deliver commodities from continental US depots to field locations as close as possible to the ultimate Army user. Axiomatic to this approach will be the elimination, or severe scaling down, of the many levels of intermediate supply points which have classically stood between the basic suppliers and ultimate user of commodities in the military area of operations. This scaling down of the "logistics tail" will certainly contribute measurably towards an increase in tactical strategic mobility, a factor which will be all-important in the future. This reduction of the "logistics tail" will also increase significantly the ratio of combat troops to support troops, a feat all of us as taxpayers and as military managers would like to accomplish.

This general military strategy demands a complementary communications strategy to meet the ever growing requirements of our forces in the field. Our need for mobility is best illustrated by future objectives which state the needs for movement of command posts and headquarters at various Army echelons as shown in Appendix III. Set up and tear down times of zero minutes and movements every one to three hours for company sized headquarters can only be obtained with some type of wireless system.

As we become increasingly sophisticated in our technology and with state of the art prices dropping as a result of quantity production of large scale integrated circuitry, we should be able to provide radio and wire communications services which will be better by orders of magnitude. We should be able also to cut out sizeable segments of our "logistics tail" by reducing weight, cubage, materiel costs, and personnel for supply and maintenance to say nothing of reductions in operating costs.

One of the ways of reducing the "logistics tail" and providing increased mobility and responsiveness will be by eliminating or greatly reducing wire and cable dependent communications systems in favor of sophisticated, secure, lightweight, low cost, and easy to operate wireless communications systems. These systems will replace or augment, especially in the lower echelons, our current manually switched multichannel radio and cable systems with their cumbersome time and materiel consuming wire and cable interconnections between shelters and to headquarters subscribers.

The cost and time equations associated with our profession are changing. We will be vitally interested in the development of the laser and wisp-like fiber optic cable multichannel systems. We also need to reduce or eliminate the complex usage of internal wiring of our command posts and headquarters elements. We will be unable much longer to afford to tie our forward maneuver elements of the Infantry, Artillery, and Armor to the current heavy, bulky, and vulnerable plastic coated common denominator for all of our communications systems.

We have the technology and techniques today which will enable us to provide the kind of wireless systems alluded to previously. We know that the hardware and software for totally secure, multichannel and multiple user direct dial, wireless systems can be provided. The parts densities of several hundred thousand per cubic inch which are possible at low cost today, coupled with the logic techniques which are also state of the art, are making current radios obsolete and are pointing toward the reduction in large scale dependence on the current bulky, costly and cumbersome wire and cable systems.

From the military standpoint, the message is very clear if we are indeed to obtain maximum mobility at minimum cost, where minimum cost considers not only procurement cost but the costs in time, material, money, and manpower of handling, shipping, stockage, financing, installation, recovery, and maintenance to say nothing of the possible waste of scarce raw material resources. There is, thus, no doubt that a large segment of our reliance in the Army on wire and cable can be eliminated.

V. PROBABLE FUTURE ARMY NEEDS FOR WIRE AND CABLE

The answer to the question posed in our title hinges on what is needed to make the best use of our future smaller wire and cable systems. In general, these systems probably will be used in the higher echelons for interconnecting shelter mounted radio terminals, multiplexers, patching panels, switching centrals, and operations centers, for the distribution of user loops, and to a very limited extent, for an alternate means to backup long-haul multichannel radio links.

There thus will be a continuing need for improvement of current items and means for their installation, maintenance, and recovery. For example, better 26-pair cable and connectors having less weight, crosstalk, and leakage with greater reliability and ruggedness will be needed for intershelter connections and loop distribution systems to carry four-wire telephone and data circuits in the larger headquarters areas. Improved single-pair and four-wire field wire and twin-coaxial cables will be needed, again with lighter weight,

better connectors and splicing means, more ruggedness, and adequate shielding from the effects of electromagnetic pulses. Lighter weight, more durable power supply cables will be needed for use in communications complexes. Other needed improvements include up-to-date and more efficient means for line installation, overhead support, burying, testing, maintenance, repair, and recovery of wire and cable lines. All of these improvements should result in lower costs and better communications. We will be relying heavily upon the wire and cable industry with its broad imagination for technological advances in these areas.

While there are few approved needs for the development of entirely new Army wire and cable systems, future requirements are being considered and needs will likely be identified for adaptations of items being developed for commercial use. These future Army wire and cable items will have to be developed as segments of integrated systems which would include repeaters, multiplexers, cable drivers, and means for installation, maintenance, and if necessary, recovery. For example, we hope the wire and cable industry will develop inexpensive cable systems, possibly using fiber optic cables, which will be truly expendable and not worth recovering or stealing even after brief periods of use. Also, we foresee the commercial development of easily installed, economical, multiplexed cable distribution systems which will be readily usable by the Army for carrying secure digital circuits in headquarters installations. In the immediate future, we will likely request industry to develop a small, lightweight, field distribution cable of about 52 quads with connectors for use in carrying analog and digital signals from large automatic electronic switching centrals scheduled for introduction in a few years. For the foreseeable future, commercial standard plastic insulated wire and cable needed for base camps and other semipermanent facilities in rear areas will continue to be obtained from the most up-to-date off-the-shelf commercial stocks.

VI. CLOSING REMARKS

The answer to the question posed in the title of this paper, "What Future Is There For Wire And Cable In Army Field Communications?" can then be stated in summary as follows:

"The US Army's quantitative need for wire and cable can be expected to decrease considerably in the future while our qualitative requirements are likely to increase. The Army will continue to rely heavily upon the wire and cable industry for evolutionary improvement of our remaining wire and cable facilities, construction methods, and related tools and equipment. Within present priority and budget constraints, the Army will be able to fund only a few entirely new wire and cable developments. Hence, we will of necessity be depending upon industry for most of our new developments."

In view of this answer, the ideas and help of the wire and cable industry in defining and meeting our future needs are earnestly sought. It will be to our mutual advantage to work together on the improvements and problems described herein. The US Army, industry, and our country are sure to benefit from such cooperation.

APPENDIX I

STANDARD ARMY FIELD WIRE AND CABLE

A. Lightweight Assault Wire
   1. Nomenclature: Telephone Cable WD-36/TT.
   2. First Standardized: January 1965.
   3. Applications: Short range voice circuits in forward areas, principally for one-time use with sound powered telephones.
   4. Electrical Characteristics:
      a. Attenuation at 1 KHz and 60° F:
         Wet, 5.9 db per mile
         Dry, 3.6 db per mile
      b. Resistance at 60° F: 310 ohms per conductor mile.
      c. Normal Frequency Range: dc to 4 KHz.
   5. Physical Characteristics:
      a. Construction: Parallel duplex pair (zip cord).
      b. Overall Covering: None.
      c. Conductor Insulation: Low desnity polyethylene.
      d. Conductor: Solid #23 aluminum.
      e. Breaking Strength: 25 pounds.
      f. Weight: 8.5 pounds per mile.
      g. Overall Size: .036 by .072 inches.
   6. Connectors or Splices:
      a. Splices: Zip, skin, twist, and tape.
      b. Connectors: None.
      c. Tools: Bare hands and/or knife and pliers (TE-33).
   7. Packaging:
      a. Dispenser MX-6895/TT: 1/4 mile, 3 pounds, $12.
      b. Dispenser MX-6894/TT: 1/2 mile, 5 pounds, $17.
   8. Cost: $25 per mile.

B. Single-Pair Field Wire
   1. Nomenclature: Wire WD-1/TT.
   2. First Standardized: February 1945.
   3. Applications: Voice, teletypewriter, and data; loops and trunks (two-wire).
   4. Electrical Characteristics:
      a. Attenuation at 1 KHz and 60° F:
         Wet, 2.5 db per mile.
         Dry, 1.5 db per mile.
      b. Resistance at 60° F: 117 ohms per conductor mile.
      c. Normal Frequency Range: dc to 4 KHz.
   5. Physical Characteristics:
      a. Construction: Twisted pair.
      b. Overall Covering: None.
      c. Conductor Insulation: Polyethylene with nylon jacket.
      d. Conductor: 7 strands .011 inches each, 4 tinned copper plus 3 galvanized steel.
      e. Breaking Strength: 200 pounds.
      f. Weight: 50 pounds per mile.
      g. Overall Size: .170 inches (.085 inches per conductor).

6. Connectors or Splices:
   a. Splices: Skin, knot, and tape for each conductor.
   b. Connectors: One-step insulated and crimped splicing sleeve for each conductor.
   c. Tools: Splicing Sleeve Compressing Tool TL-582/G (part of MX-356/G); knife and pliers (TE-33).
7. Packaging:
   a. Spool DR-8A: .25 miles, 14 pounds, $19.
   b. Dispenser MX-306A/G: .5 miles, 26 pounds, $45.
   c. Reel RL-159/U: 1 mile, 66 pounds, $57.
   d. Reel DR-5: 2.5 miles, 154 pounds, $131.
8. Cost: $50 per mile without reels.

C. Four-Wire Field Wire
1. Nomenclature: Telephone Cable WF-16/U.
2. First Standardized: (Limited Production) August 1966.
3. Applications: Voice, teletypewriter, and data; loops and trunks (four-wire).
4. Electrical Characteristics:
   a. Attenuation at 1 KHz and 60° F:
      Wet, 2.6 db per mile.
      Dry, 2.0 db per mile.
   b. Resistance at 60° F: 140 ohms per conductor mile.
   c. Normal Frequency Range: dc to 4 KHz.
5. Physical Characteristics:
   a. Construction: Two Parallel duplex pairs twisted together.
   b. Overall Covering: None.
   c. Conductor Insulation: Polyethylene (.125 by .083 inches overall per pair, one pair dark colored with identifying ridge).
   d. Conductor: 7 strands #32 cadmium copper alloy.
   e. Breaking Strength: 200 pounds (100 per pair).
   f. Weight: 62 pounds per mile.
   g. Overall Size: .25 inches (max).
6. Connectors or Splices:
   a. Splices: Zip each pair, skin, knot and tape.
   b. Connectors: None.
   c. Tools: Knife and pliers (TE-33).
7. Packaging:
   a. Reel RL-159/U: .8 mile, 80 pounds, not issued.
   b. Reel DR-5: 1.0 mile, 199 pounds, $116.
8. Cost: $110 per mile without reels.

D. 26-Pair Field Cable
1. Nomenclature: Telephone Cable Assembly CX-4566/G.
2. First Standardized: January 1966.
3. Applications: Voice, teletypewriter, and data; shelter interconnections and local loop distribution (two and four-wire).
4. Electrical Characteristics:
   a. Attenuation at 1 KHz and 60° F: 2.7 db per mile.
   b. Resistance at 60° F: 163 ohms per conductor mile.
   c. Normal Frequency Range: dc to 4 KHz.
5. Physical Characteristics:
   a. Construction: 26 twisted pair with overall jacket and U-185/G universal connector on each end.
   b. Overall Covering: Polyvinyl chloride jacket.
   c. Conductor Insulation: Polyethylene.
   d. Conductor: #24 (7 strands .008 inch, 6 tinned copper, 1 galvanized steel).
   e. Breaking Strength: 800 pounds.
   f. Weight: 1100 pounds per mile (no connectors); CX-4566/G, 250 feet with 2 connectors, 54 pounds.
   g. Overall Size: .625 inches.
6. Connectors:
   a. Splices: Normally not spliced.
   b. Connectors: Type U-185/G waterproof universal 26-pair quick connectors, 2 pounds each.
   c. Tools: None.
7. Packaging:
   a. Reel RC-435/U: 250 feet, 68 pounds.
   b. In Coils: 25 feet, 9 pounds.
   c. Stub: 15 feet, 5 pounds, connectors on one end, other end fanned out for connecting to termianl strips, Telephone Cable Assembly CX-4760/G.
8. Cost: CX-4566/G, 250 feet, $87. ($107 on RC-435/U) or $1850 per mile installed without reels.
9. Remarks:
   a. Distribution Box J-1077/U provides a 26-pair bridging terminal strip at the junction of two CX-4655/G or a terminal strip for one CX-4566/G, $91.
   b. Distribution Box J-2317/U provides a frame with terminal strip boxes for terminating and cross connecting four CX-4566/G, $500.

E. Spiral-Four Field Cable
1. Nomenclature: Telephone Cable Assembly CX-1606/G.
2. First Standardized: September 1952.
3. Applications: Carrier telephone systems of 4 and 12 voice channels; single channel voice, teletypewriter, and data; mostly for trunks.
4. Electrical Characteristics:
   a. Attenuation at 68° F (in db per mile):

FREQUENCY	NON-LOADED	LOADED
1 KHz	1.3	.78
20 KHz	3.0	.88
70 KHz	4.0	---

   b. Resistance at 68° (in ohms per conductor mile).
      43.3 non-loaded
      46.3 loaded
   c. Normal Frequency Range:
      dc to 70 KHz non-loaded.
      dc to 20 KHz loaded.
5. Physical Characteristics:
   a. Construction: Spiral-four (star) quad with static shield, wire braid, and overall jacket.

b. Covering: Polyethylene inner jacket, carbon cloth tape static shield, stainless steel braid for protection and strength, thermo-plastic outer jacket.
c. Conductor Insulation: Polyethylene.
d. Conductor: #19, 7 strands .014 inch copper.
e. Breaking Strength: 700 pounds.
f. Weight: 390 pounds per mile (including 8 connectors but without loading coils or reels).
g. Overall Diameter: .370 inches.

6. Connectors:
   a. Splices: Normally not spliced.
   b. Connectors: Electrical Connecting Plug U-176/G universal connector furnished on each end of each 1/4 mile and 100 foot long CX-1606/G.
   c. Tools: None.
7. Packaging:
   a. Reel DR-15B: .25 miles, 137 pounds, $132.
   b. Coil: 100 feet, 7.5 pounds, $22.
   c. Stub: 12 feet, 2 pounds, connector on one end, other end fanned out, Cable Assembly CX-1512/U, $8.
8. Cost: $496 per mile without loading coils.
9. Remarks:
   a. Telephone Loading Coil CU-260/G (6 millihenry) is placed at the end of each 1/4 mile length of CX-1606/G to reduce attenuation for 4-channel carrier and voice uses. Cost $9.60 each.
   b. To be superseded by twin coaxial field cable.

Twin-Coaxial Field Cable

1. Nomenclature: Special Purpose **Electrical** Cable Assembly CX-11230/G.
2. First Standardized: April 1969.
3. Applications: Voice, teletypewriter, and data on 6-, 12-, 24-, 48-, and 96-channel systems using secure pulse code modulated time division multiplexing.
4. Electrical Characteristics:
   a. Attenuation at 2.3 MHz and 60° F: 38 db per mile.
   b. Resistance at 60° F: 88 ohms per mile (center conductor); 30 ohms outer conductor.
   c. Normal Frequency Range: dc to over 5 MHz (5 megabits).
5. Physical Characteristics:
   a. Construction: Twisted pair of coaxial cables with a reinforced overall jacket and a universal connector on each end of a 1/4 mile length.
   b. Covering: High density polyethylene outer jacket and copper-clad steel braid for shielding and strength.
   c. Coaxial Construction: Copper center conductor #22 (7 strands, .010 inch), high density polyethylene dielectric, #36 copper braided outer conductor, and low density polyethylene jacket.
   d. Breaking Strength: 600 pounds.
   e. Weight: 310 pounds per mile (no connectors); CX-11230/G, 1/4 mile with 2 connectors, 80 pounds.
   f. Overall Size: .364 inches.
6. Connectors or Splices:
   a. Splices: Normally not spliced.
   b. Connectors: UG-1870/G waterproof universal twin coaxial quick connectors, 1 pound each.
   c. Tools: None.
7. Packaging:
   a. Reel DR-15B: .25 miles, 120 pounds, $147.
   b. In Coils: 100 feet, 8 pounds, $24.
   c. Stub: See remarks.
8. Cost: $556 per mile without reels.
9. Remarks:
   a. Cable Assembly CX-10734/G is a 4-foot length of cable with a connector on one end and two coaxial connectors on the other end for connecting to shelters, equipment, and Cable CX-4245 which is being replaced by CX-11230.
   b. Cable systems for 6-, 12-, 24, and 48-channels can be installed with 40 miles between terminals and/or attended repeaters with unattended repeaters at one mile intervals (power fed over the cable). Cable systems for 48 and 96 channels can be installed with 5 miles between terminals and/or line of sight radio relay, troposcatter, or satellite terminals with unattended repeaters at 1/2 mile intervals.
   c. This cable will eventually supersede spiral-four field cable.

APPENDIX II

ARMY LINE CONSTRUCTION EQUIPMENT

A. Line Construction Truck

Truck V-17/MTQ was first standardized in October 1945. It is a military, 2 1/2 ton, 6 x 6, truck chassis with a modified commercial construction truck body including storage space for construction supplies and tools, pole derrick, revolving overhead platform , pole jack, hoisting winch, and collapsible power reel. It is used by wire and cable installation units at corps, field army, and communication zone levels. Dimensions: 276 inches long x 94 inches wide x 120 inches high; weight 16,500 pounds as issued; cost $13,000..

B. Earth Borer Truck

Truck V-18/MTQ was first standardized in October 1945. It is a military, 2 1/2 ton, 6 x 6, truck chassis with rear mounted earth boring and pole setting equipment driven by the truck engine. It is equipped with augers of 9 inch, 12 inch, 16 inch, 20 inch, and 30 inch diameters for boring holes to a depth

of 10 feet. It is used by wire and cable installation units at corps, field army, and communication zone levels. Dimensions: 330 inches long x 88 inches wide x 107 inches high; weight 17,200 pounds; cost $24,000.

C. Pole and Reel Trailer

Trailer V-120/GT was first standardized in April 1965. It is a 3 1/2 ton, 2-wheel trailer with axle for cable reels and with bolsters and extendable tongue for pole hauling. It accommodates reels up to 37 inches wide x 84 inches diameter. It is used at division, corps, field army, and communication zone levels. Dimensions: 149 inches long x 94 inches wide x 118 inches high; weight 6,000 pounds; cost $1870.

D. Cable Plow

Underground Cable Layer LC-236/MT was first standardized in August 1959. It is a 2-wheel trailer-type plow for burying six pairs of field wire or one spiral four cable or one twin coaxial cable to depths of 10 inches at speeds of 5 miles per hour when towed by 1/4-, 3/4-, or 2 1/2-ton trucks. It is used by wire and cable installation units at corps, field army, and communication zone levels. Dimensions: 103 inches long x 71 inches wide x 68 inches high; weight 1,100 pounds; cost $4100.

E. Reeling and Dispensing Equipment

1. Cable Reel Axle RL-27, standardized February 1936, is an axle with two handles and a removable crank for pay-out and pick-up of wire on Reel RL-159 when carried by two men. Used at all levels. Cost $20.

2. Hand Cable Reeling Machine RL-31, standardized February 1936, is a collapsible 'A' or 'H' frame with one divided axle for pay-out or pick-up of wire and cable on Reels DR-5, DR-15, or two RL-159. Includes 2 crank handles and brakes. As a 'H' frame can be carried by two men. As an 'A' frame can be mounted on a vehicle bed or tailgate or on the ground. Used at all levels. Cost $148.

3. Cable Pay-Out Reel RL-128/G, standardized April 1951, is a rotating framework with brake for unreeling line wire from coils of varying diameters up to 26 inches overall. Spool diameter is adjustable. Overall diameter 32 inches, height 10 5/8 inches. Can be used in vehicles or on ground in multiples for pulling several wires at one time. Used above corps level. Cost $44.

4. Motor Driven Cable Reeling Machine RL-172/G, standardized August 1959, is a 24-volt electric motor driven, single axle machine for pay-out and pick-up of wire on one reel RL-159/U when mounted vertically on the tailgate or horizonatlly on the floor of 1/4-ton or 3/4-ton trucks. Used within division. Cost $308.

5. Engine Driven Cable Reeling Machine RL-207/G, standardized January 1961, is a gasoline engine driven unit with two separately controlled axles for pay-out and pick-up of field wire and cable on two reels DR-5 or DR-15 or four reels RL-159/U when mounted in 3/4-ton or 2 1/2-ton trucks or on the ground. Used in all areas. Cost $920.

6. Reel Equipment CE-11, standardized September 1930, is a man-carried reeling unit RL-39 with a sound powered telephone TA-1/PT. Reel unit holds one DR-8A with 1/4 mile of field wire WD-1/TT used to pay-out or pick-up wire; can be handcarried or strapped to chest. Used in forward division areas. Cost $38.

7. Wire and Cable Dispensers MX-306A/G, MX-6894/TT, and MX-6895/TT are lightweight, expendable, canvas canisters of field wire wound in a toroidal coil with a hollow core so that the wire can be pulled from the center of the core. Wire may be payed out from manpack or vehicle. Used in forward division areas. All are approximately 15 inches in diameter by 5 inches high. MX-306A/G holds 1/2 mile WD-1/TT, MX-6894/TT holds 1/2 mile WD-36/TT, and MX-6985/TT holds 1/4 mile WD-36/TT (see Appendix I, items B and A, respectively for additional data).

8. Reels, spools, and drums are described in the following table:

TYPE	FIRST STDZN	DMNs (INCHES) OD	LGTH	WT LBS	COST
DR-5	Oct 42	19.3	18	34	$ 5.80
DR-8	Dec 44	9	8	2	$ 6.90
DR-15B	Jun 42	19.5	18	40	$ 8.00
RC-435/U	Sep 61	22.5	7.5	18	$19.80
RL-159/U	Jun 51	19.3	7	18	$ 7.00

F. Metal Poles

Metal Line Construction Poles AB-308/G (steel) and AB-309/G (aluminum), standardized September 1954, are 26 1/4 foot long sectional (four 7-foot, nesting sections) line poles to support two-pair open wire line plus two spiral-four cables for use as hasty constructions in tropic communication zone areas. Diameter at top 3 inches, bottom 6 3/4 inches, weight: AB-308/G is 113 pounds, AB-309/G is 77 pounds. Cost: AB-308/G, $100; AB-309/G, $120.

APPENDIX III

COMMAND-POST DISPLACEMENT OBJECTIVES

ECHELON	TIME IN MINUTES SET-UP/TEAR DOWN	TIMES PER DAY
Company HQ	0	8-24
Battalion HQ	5	6-8
Brigade HQ	15	3-5
Division HQ	30	1-3

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FIBER OPTICS: AN OVER-VIEW OF A FUTURE ALTERNATIVE TRANSMISSION MEDIUM

by

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ABSTRACT

Recent advances in low-loss optical fiber research have stimulated consideration of optical fibers as an alternative transmission medium to complement conventional cables in many area of application. This paper will review what an optical fiber is, how it works and what its transmission capabilities are.

INTRODUCTION

The feasibility of using an optical fiber as a short, medium or long distance transmission medium has been greatly enhanced by fabrication of low-loss ($\leq$ 20 db/km) optical fibers at Corning Glass Works[1] and Bell Laboratories.[2] These recent discoveries have stimulated interest in the field of fiber-optic communications. Because of small physical size and large bandwidth capability, optical fibers have numerous potential applications in communication systems. Some of these are:

(1) Interconnections of communication equipment in a building over distances of a few hundred feet to a few thousand feet (for example, on-premises connection of telephones; high-capacity links in a central office; or communication between computers).

(2) Interoffice trunks over distances of a few miles with channels of low to medium capacity.

(3) Intercity routes over hundreds of miles requiring medium to high capacity transmission.

In short, it appears that optical fibers have possibilities wherever twisted-wire pairs or coaxial cable are used for communication. With this motivation in mind, the remainder of this paper will address itself to a description of an optical fiber, its transmission capabilities and its many attractive features.

WHAT IS AN OPTICAL FIBER?

An optical fiber is a dielectric waveguide composed of materials of differing indices of refractions.[4] Often the geometry of the fiber is as shown in Figure 1. There is an inner cylinder of refractive index n_1, called the core, surrounded by a cylindrical shell of lower refractive index n_2 called the cladding. The core is typically a few microns to 100 microns. The cladding diameter is a few tens of microns to about 200 microns. To give the reader an idea of how the size of an optical fiber compares with wire gauges, a 26 gauge wire is about 400 microns in diameter, a desirable cladding diameter of an optical fiber is about 125 microns. So an optical fiber is a small, flexible transmission medium with a diameter of about 1/3 to 1/4 that of 26 gauge wire. The resulting optical cable made from glass fibers will have a higher packing density (number of fibers per cable cross-section) than that of paired cable.[5] This factor is a very important one in an urban situation where duct space is at a premium and additional duct runs are very costly.

WHAT ARE THE MEANS OF OPERATION AND TRANSMISSION CHARACTERISTICS OF AN OPTICAL FIBER?

The operation of an optical fiber can at least heuristically be described by the

principle of total internal reflection.[6] Consider an interface between two dielectric media of indices of refraction n_1 and n_2 where $n_1 \geq n_2$ as shown in Figure 2. In general, if a monochromatic plane wave is incident upon the interface, there will be both reflected and a refracted (transmitted) wave. If however, the indicent wave satisfies the criterion that $\sin \theta_1 \geq n_2/n_1$ there will be no transmitted wave and total reflection of the indicent energy will occur. One can from this simple principle of total internal reflection, picture the waveguiding mechanism of a multi-mode optical waveguide. Figure 3 shows how a plane wave is guided down a dielectric slab guide. This is of course a simplified explanation describing the operation of an optical fiber. An analysis of this structure reveals that there are a number of natural distributions of the electromagnetic field or modes that will propagate.[7] Each mode has its own attenuation constant and propagation delay. The number of modes can be approximately obtained by the formula shown in Figure 4.[8] Observe that the number of modes a fiber can support is proportional to the core diameter and to the difference between core and cladding refractive indices. If the parameters are chosen such that many modes can be propagated, it is called a "multi-mode fiber". To appreciate how the transmission characteristics of a multi-mode fiber differ from that of a single mode fiber it is important to understand a number of terms that are used to evaluate the optical properties of a fiber.

1. Transmission Loss - Loss occurs in a guide when energy is extracted from the propagating field and reradiated out of the guide or converted to heat. There are three main sources of loss in an optical fiber:

   (a) Absorption Loss - conversion of energy to heat by impurity atoms in the glass or liquid.

   (b) Waveguide Scattering - scattering of light due to a "rough" interface between the core and cladding or other imperfections in the guide.

   (c) Rayleigh Scattering - this scattering is caused by minute dielectric inhomogenities in the glass or liquid which are small compared to a wavelength. Rayleigh scattering occurs almost uniformly in all directions and represents the minimum possible loss in a guide.

2. Pulse Dispersion - A measure of pulse dispersion in a dielectric guide can be obtained by observing how a pulse is broadened as it propagates down the guide. There are two basic causes of dispersion in an optical fiber:

   (a) Material Dispersion - the refractive index of the core is frequency dependent, consequently each frequency component of the message travels at a different speed. For ordinary glasses, this dispersion is a fraction of a picosecond/km for every gigahertz of source bandwidth.

   (b) Mode Dispersion - the power in each mode of a multi-mode fiber travels at a different velocity. The rays corresponding to each mode travel at different angles, and the higher the order of the mode, the longer the overall path becomes. For a 1% index difference between the core and the cladding, a signal with a bandwidth in the order of 50 MHz can be sent through a 1 km guide without excessive distortion.

Because of mode dispersion the bandwidth of a multi-mode fiber is much less than a single mode type. A review of the characteristics of single and multi-mode fibers and their areas of application are shown in Figure 5. Observe that for a single mode fiber:

1. A coherent source is required since the amount of incoherent power that can be coupled into a guide is proportional to the number of modes it can guide.

2. It is a high capacity channel.

3. It may be difficult to splice due to small core size.

Observe that for a multi-mode fiber:

1. Both coherent and incoherent sources can be used.

2. It can be used as a low to medium capacity channel.

3. It can be more easily spliced because of its larger core size.

ATTRACTIVE FEATURES OF OPTICAL FIBER TRANSMISSION

The areas of application for a fiber optic system as cited in Figure 5 suggest that optical fibers can be potentially used wherever twisted-wire pairs and coaxial cables are used for communication. It is interesting to note the attractive features than an optical fiber system would have:

1. Small Size - The cable packing density of a fiber optic cable will be about 9 times greater than that of a 26 gauge twisted-pair cable. This is important for interoffice trunk applications in metropolitan areas.

2. Small Bending Radius - This feature is especially important in on-premise wiring applications.

3. Lightening protection may be unnecessary in a fiber optic cable.

4. Flexibility - An optical fiber can carry a single voice channel or a highly multiplexed channel, depending on the terminal electronics.

5. High Capacity - Because of their large bandwidth, optical fibers can transmit large amounts of information.

6. Potentially Economical - Glass is plentiful and cheap. However, inexpensive fibers of adequate optical quality are yet to be manufactured in large quantities.

Because of its many attractive features and potential applications a fiber optic cable may be one of the media satisfying the future needs of the wire and cable industry.

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Dr. Cherin joined Bell Laboratories in 1965 as a Member of Technical Staff. In the Transmission Media Laboratory he has worked on various projects related to the characterization of transmission lines. Since June, 1971 he has been working on problems related to the development and characterization of a fiber optic communications cable.

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THE GEOMETRY OF A TYPICAL OPTICAL FIBER

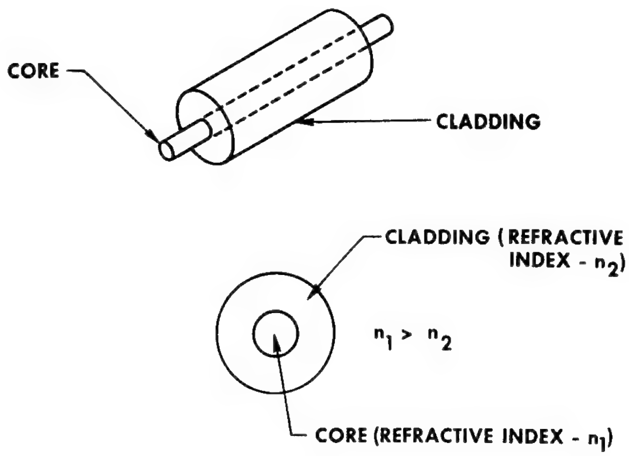


FIGURE 1

REFLECTION AND REFRACTION AT A DIELECTRIC INTERFACE

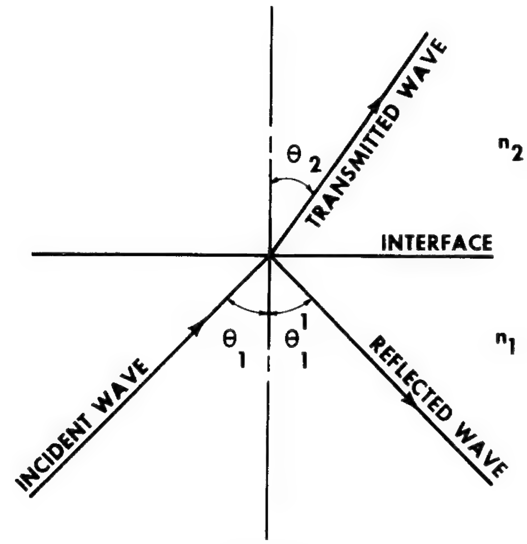
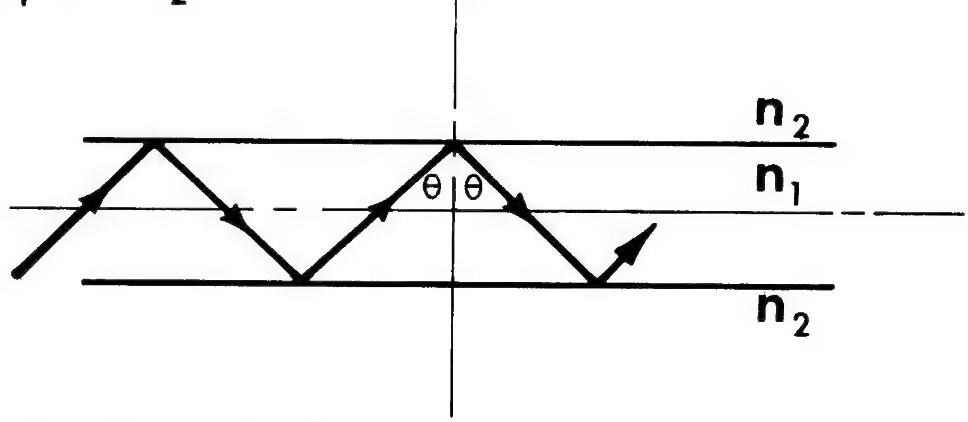


FIGURE 2

$(n_1 \geq n_2)$



TOTAL INTERNAL REFLECTION OCCURS WHEN $\sin\theta > \frac{n_2}{n_1}$

FIGURE 3

$$N = \frac{k\, D_1^2}{\lambda^2}\left[n_1^2 - n_2^2\right]$$

N= NUMBER OF PROPAGATING MODES

D1 = CORE DIAMETER

λ = WAVELENGTH OF PROPAGATING ENERGY

n_1 = CORE REFRACTIVE INDEX

n_2 = CLADDING REFRACTIVE INDEX

k = PROPORTIONALITY CONSTANT

FIGURE 4

FIBER TYPE	SOURCE TYPE	CHANNEL CAPACITY	CHANNEL LOSS	SPLICING	AREAS OF APPLICATION
MULTI-MODE FIBER	INCOHERENT OR COHERENT SOURCES	LOW TO MEDIUM CAPACITY	< 20 db/km	DESIRABLE CORE SIZE FOR SPLICING	(a) INTERCONNECTIONS OF COMMUNICATIONS EQUIPMENT IN A BUILDING OR BETWEEN BUILDINGS (b) INTEROFFICE TRUNKS OVER DISTANCES OF A FEW MILES
SINGLE-MODE FIBER	COHERENT SOURCE ONLY	HIGH CAPACITY	< 20 db/km	SPLICING MAY BE DIFFICULT DUE TO SMALL CORE SIZE	(c) INTERCITY ROUTES (a) OR (b) ABOVE WHEN HIGH CAPACITY CHANNEL REQUIRED

FIGURE 5

STUDY OF AN ALL OPTICAL COMMUNICATIONS SYSTEM FOR TRUNKING, SWITCHING AND DISTRIBUTION OF WIDEBAND SIGNALS

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ABSTRACT

A hypothetical all-optical communications system for trunking, switching, and distributing wideband signals between subscriber main stations is described and analyzed. Multimode optical fibers using LED's in the distribution plant, and single mode optical fibers using mode-locked Nd:YAℓG lasers in the trunk plant form the basis of the system approach. All signal transmissions are pulsed, and repeaters are required to make up signal losses in distribution and trunking. The most critical optical component required in terms of low cost in this communications concept is the distribution photodetector. Each subscriber station consists of equipment totaling 32 MHz in base bandwidth.

1. INTRODUCTION

Optical communications, by means of optic fibers, lasers, light emitting diodes, avalanche detectors, and modulators, may become preeminent in telecommunications in the next two decades. The promise that this technology brings is wide bandwidth at low cost. Today, unit costs for some of the components (e.g., Nd:YAℓG laser $3500; Si Avalanche diode detector and biasing circuit $1500) are discouragingly high, but with several sectors of the industry showing serious interest in this mode of communications, notably the GPO,[1,2] AT&T,[3] Philips,[4] costs for components should come down drastically. A.D.Little[5] predicts cost competitiveness for optical single function devices, plus the arrival of integrated optics within five years.

Demands for wider bandwidth per subscriber channel come from the gradually increasing[6] usage of Picturephone® using the "Telco" network, and from the "new town" industry.[7] A recent forecast[6] made for the telephone industry predicts a breakthrough in distribution technology. Optical communications may be the candidate that could fulfill this prediction.

This paper analyzes a hypothetical optical communications system which provides point-to-point switched broadband service between subscriber main stations. Included is an approach to wideband distribution and office-to-office trunking which, except for the bandwidth, is not unlike the switched voiceband service to Telco subscribers. Optical trunks connect between switches, to provide medium- and long-distance communications for the subscriber stations connected to the various switches. Optical distribution lines from local switches to subscribers are suggested for this hypothetical system.

Costs of components must drop and improvements in the reliability of the components are mandatory, especially in LED's, detectors, modulators and lasers before such a communication system would have widespread use.

2. SYSTEM DESCRIPTION

System topology follows the scheme suggested in Figure 1. All transmission, distribution, and switching are done using the equivalent of four-wire full duplex. Pulsed optical signals are propagated in the system. Subscriber main stations are served over multimode optic fiber cables from the central office. This allows low-cost light emitting diodes to be used for generating the pulsed optical carrier from each subscriber main station. Central offices contain optical switching equipment, lasers, light emitting diodes, modulators, and detectors. Single-mode fiber optics

connect between central offices. Electronics are required for converting the relatively low-speed distribution pulse frequency to the high-speed interoffice trunk pulse frequency. These circuits are used as head end trunk equipment in each central office.

If distance between main stations and central offices exceeds signal loss limits, then distribution repeaters are used. Central offices interconnect with each other over optic fiber pathways, with repeaters used as required. These repeaters are "trunk repeaters" and differ distinctly from distribution repeaters.

Optic fibers are individually encapsulated in plastic sheaths,[8] and many of these are brought together in one cable. These cables are placed in ducts in the same manner as telephone cables.

2.1 Subscriber Main Stations

Main stations consist of the subscriber terminal apparatus and electro-optical multiplex and demultiplex devices. The maximum complements of subscriber terminal devices are those summarized in Table 1. Subscriber bandwidths for transmitting and receiving using FDM and TDM are compared also. Figure 2 depicts a typical subscriber loop, serving the full complement of terminal devices.

Time-division-multiplexed pulsed transmission is assumed in the optic part of the system. This option has been taken because the optic fiber medium exhibits between 10 and 20 dB/km[9] loss and is dispersive. BTL has reported a 14 dB/km multimode fiber,[3] and more recently, Corning Glass is reported to have developed a 4 dB/km fiber.[10] The 14 dB/km figure has been used in the end-to-end loss calculations which are summarized later. Repeaters will be needed in the system and will be spaced at distances that provide 20 dB or better signal-to-noise ratio. Use of pulsed transmission relaxes the linearity requirement on the receiver/retransmitter.

Referring to Table 1, the transmission bit rate using eight-level PCM encoding of each terminal device is slightly greater than 67 Mb/s; the receive bit rate is about 204 Mb/s. Framing and sync pulses are inserted which bring the transmission rate to a convenient 72 Mb/s, and the receive bit rate to 216 Mb/s. Nine time slots are suggested for transmitting, and 27 time slots are suggested for receiving. Three receiving fibers are used so that the bit rate per fiber need only be $216 \div 3 = 72$ Mb/s. As conceived, the receiver fibers are assigned as follows:

Fiber 1	Wideband Color Pictel; 2 Voice Telephones, Fire/Intrusion Alarm
Fiber 2	Color Video Receiver 1; FM Receiver
Fiber 3	Color Video Receiver 2; Data Receiver

This compromise was reached on the basis of optical detector availability and low cost. Relatively low cost[11] devices exist now which can detect optical signals at -42 dBm, at S/N = 10 in the 250-MHz range. These devices have been used in this analysis of the distribution repeater, central office, and main subscriber station detectors.

Broadband services are oriented "toward" the subscriber as observed by comparing the bit rates to and from each full complement main station. Preliminary comparisons of costs of light sources and wideband detectors resulted in the proposed unbalanced distribution system shown in Figure 2. As previously mentioned, it consists of one optic fiber from the main station and three optic fibers to the main station. These are conceived as analogous to the four "drop wires" now used in the conventional telephone system. A light emitting diode operating in the visible spectrum is directly modulated by the electronic output of the transmitter-multiplexer. A coupling device[12] labeled "C" guides the light from the LED into the multimode fiber. Signals that are to be fed to the terminal devices arrive over three multimode fibers, and are coupled to silicon photodiodes, each labeled "detector". The electrical outputs from each detector are amplified, and these signals provide inputs to the receiver-demultiplexer. The function of the demultiplexer is to divide up the pulse trains, convert them to analog signals, and distribute these to the appropriate terminal devices.

TABLE 1

BANDWIDTH REQUIREMENTS FOR TERMINAL DEVICES

		FDM		TDM (8-bit)	
		Transmit (MHz)	Receive (MHz)	Transmit (Mb/s)	Receive (Mb/s)
2	Voice Telephones	0.016	0.016	0.128	0.128
1	Fire/Intrusion Alarm	0.0003		0.00015	
1	Wideband Color Pictel Video	6.0	6.0	67.2	67.2
2	Color Video Receivers		12.0		134.2
1	FM Receiver		0.300		2.4
1	50 kbit Data	0.0003	0.100	0.00015	0.05
	Guard Bands Between Channels	1.9834	5.584	4.6717	11.822
	Total Bandwidth	8.0	24.0	72.0	216.0

2.2 Distribution Repeater

As the optical pulses propagate along the glass fiber, they suffer losses due to scattering, bends, tapers, periodic variations, and ellipticity[13] in the core and at the boundary, and dispersion due mainly to multimode path length[14] differences. Repeaters serve the function of restoring the signals with minimum bit error and relaunching them in the required directions. A distribution repeater is depicted in Figure 2. Couplers are needed to connect the optical signals from the fibers to the detectors, and from the LED's to the fibers. The detector converts the optical pulses to electrical pulses. Electronic signal reshaping circuits receive the detector-amplifier outputs and produce crisp trapezoidal electrical pulses for driving the light emitting diodes. Because the optical pulses as received are smeared into "Gaussian" shapes, they must also be retimed, or gated at the correct time phase. This is another function of the distribution repeater and is accomplished through the use of a local clock, whose output frequency is corrected to the long-time average incoming pulse frequency.

Feeder distribution optic fiber cables are assumed to follow rights of way (roadways, easements, etc.) from the local office out to convenient branching points or nodes. Several repeater spacings may be involved in reaching from the central office to these points. At each repeater location, up to 100 repeaters may be in place in a single housing. From the last nodal point, the fibers will spread in groups of four in order to stretch the final distance to individual main stations.

2.3 Central Office Optical Switching

Optical signals arriving at the central office from subscriber stations will be routed to their proper terminations either in the central office, out to another local subscriber, or over a trunk to a distant office. For local-to-local subscriber communications - that is, between two subscribers served by the same central office - an optical path in each direction will be established through an optical switching matrix. Figure 3 depicts a four-stage network showing the interstage topology that could be used in an optical network.

For local subscriber-to-outgoing trunk (or vice versa) communications, the subscriber's signals will be modified for conveyance on an optical trunk carrier. Trunking between central offices is conceived as using single-mode optic fiber, on which several broadband channels are time-division-multiplexed, and requires

mode-locked lasers, modulators, and beam splitters.

The broadband services that are to be provided, such as video programming and data display, FM programming and computer access, are assumed to have switching port appearances in the central office. Access to these ports by subscribers is possible by the establishment of optical pathways through the switching matrix.

Crosspoints required for switching optical channels will be required, and may follow the principles of TDM time slot interchange switching.[15] The network suggested is a "space-division" type over which pulsed optical signals are switched. Input channels will be connected to ports on the switching matrix. The switching matrix consists of an array of several stages of subswitches. A subswitch of 8 inlets and 8 outlets is illustrated in Figure 4.

Inlets and outlets of a subswitch consist of optical channels. Signals conveyed on the optical channels are sequences of "on and off" pulses, grouped in time slots, assigned to the subscribers communicating at that instant. Any subswitch functions to steer the time slot pulses from a given inlet to a particular outlet. This could be accomplished by using the principle of acousto-optic interaction[16] resulting in the acoustic beam steerers, as suggested in Figure 4. Here a light beam is brought in to the switch on one horizontal path. When it reaches the appropriate (activated) acoustic switch crosspoint, the acoustic signal applied to it (acting as an optical diffraction grating) causes the light beam to bend. Instead of passing straight through on the horizontal, it is diverted to one of the verticals. The vertical path communicates with the output port of the subswitch; this is connected to an input port of a similarly constructed switch in the second stage (rank) of switches. Following this type of topology, the switches, arranged in rows and columns, make up the switching array. Time delays are introduced as necessary to align the pulse with the proper time slots. Techniques needed include acousto-optic deflectors, optical channels in and out of each, combiners and mirrors. It is conceivable that these devices could be integrated[12] on one chip.

Control signals for selecting and operating the acoustic steerers come from a miniprocessor. Standard computer control techniques are assumed to be employed.

2.4 <u>Interoffice Optical Trunking</u>

Calls, originating from main subscriber stations connected to one central office and terminating at main subscriber stations connected to another central office, are conveyed over optic fiber trunks between the offices. Single-mode fiber would be used, carrying pulsed optical signals. Repeaters are necessary to compensate for optic signal loss and deterioration, suffered as a result of propagation over the fiber. Figure 5 illustrates the overall arrangement.

At each central office the subscriber's signals that are to be sent out over the trunks must be time-multiplexed with others. This is because the bit rate of the single-mode trunk fiber as suggested in this study is seven times the bit rate of the multimode distribution fiber. The resulting bit rate of 504 Mb/s represents a practical limit in speed of operation of modulators and detectors.[17,18] Each single-mode optic fiber would convey a 504-Mb/s pulse stream or seven 72-Mb/s subscriber channels. Figure 6 depicts the essential electro-optical hardware needed for optical trunking.

The optic source is assumed to be a mode-locked laser, tuned to generate 50-ps pulses at 504 megapulses per second. Because the mode-locked laser can be operated in the pulse mode, through optical feedback and servo loop stabilization,[19] single pulse power is enormous. The output pulse stream is split optically into approximately 100 output pulse streams. Each stream of pulses, at 504 Mb/s, is modulated by a separate modulator.[24] Modulation is binary - "on or off". Modulators have been built[20] with on-to-off ratios of 25:1 and with upper frequencies of about 500 MHz. At 504 megapulses per second, the highest frequency at which the modulators must operate corresponds to the bit sequence... 101010...requiring 252-MHz operation. The outputs from the modulators are coupled to single mode optic fibers.

2.5 <u>Trunk Repeaters</u>

Amplification of the optical pulses will be necessary to offset losses in

transmission between central offices. Practical direct optical amplification does not exist; consequently the approach used is similar to that of the distribution repeaters. The optical signals are detected - converted to electronic pulses-reshaped electronically, retimed, and used to modulate the pulsed optic output of a mode-locked laser. An electro-optical trunk repeater is depicted in Figure 7. Each laser pulse is divided optically with prisms and mirrors[12] into several dozen spatially separated lower powered pulses. Each of these pulses is guided to an individual modulator. Modulators operate as "on-off" gates to the optical pulses, and are electronically controlled from the reshaping circuits. The outputs of the modulators are coupled to the outgoing optic fibers.

Wideband silicon-Avalanche photodetectors with gain have been reported[18] and some are commercially available[21] now. Such devices have sensitivities[18] that enable signals in the 3-GHz band to be detected which are -67 dBm, and with output signal-to-noise ratios in the neighborhood of 38 dB. Using pulsed modulation, these devices can easily provide the needed detection in the single-mode system. However, they are expensive and improvements in manufacturing techniques are needed.

3. END-TO-END SIGNAL LOSS

Reference to Figure 8 will aid in following this analysis.

3.1 Distribution System

Light sources assumed for this system are light-emitting diodes operating in the visible spectrum, directly modulated by electronic pulses. Multimode optic fibers are used for communicating between subscribers and central offices. The following is a summary of characteristics of the system.

(1) Subscriber station LED-to-repeater detector.

(a) LED

Input current pulse peak:	20	mA
Diode voltage drop:	1.5	volts
Conversion efficiency:	3.3	percent
Output light power:	0	dBm
Pulse width:	6.95	nanoseconds (at half maximum)
Pulse period:	13.9	nanoseconds (72 Mb/s)

(b) Coupler loss[12] (LED to fiber): -7 dB

(c) Fiber from LED coupler to detector coupler

Unit loss:[3]	14	dB/km
Length:	2	km
Loss:	-28	dB

(d) Coupler loss (fiber to detector): -7 dB

(e) Detector EG&G Series SGD-100A

Assumed signal-to-noise ratio S/N =	10	
Received signal power	-42	dBm

(2) Repeater #(N) LED to repeater #(N+1) detector.

The sequence of devices and losses described in (1) holds for this case.

(3) Local repeater LED to central office switch and detector.

(a) LED output light power:	0	dBm
(b) Coupler loss (LED to fiber):	-7	dB
(c) Fiber loss at 1 km:	-14	dB
(d) Coupler loss (fiber to C.O. Switch):	-7	dB
(e) Central Office Switch (incoming stages)		
2 stage at 1 dB/stage loss:	-2	dB
Optical interconnections loss	-2	dB
(f) Coupler loss (switch to detector):	-14	dB
(g) Detector EG G Series SGD-100A		
Received signal power:	-39	dBm

At the central office all switched signals will be detected, amplified, and reconstructed for transmission to local subscribers, or for transmission over optical trunks.

(4) For transmission over multimode fibers to local subscribers, the sequence of devices and losses described in (1) hold.

Local subscriber to local subscriber traffic remains in the multimode propagation condition.

Local subscriber to outgoing trunk requires mode conversion from multimode fibers using LED's to single mode fibers using lasers.

Incoming trunk to outgoing trunk traffic remains in the single mode propagation condition.

Incoming trunk to local subscriber outgoing requires mode conversion from single mode to multimode.

Equipment needed for conversion between modes would be placed at the output of the optical switching network.

Signal loss will be encountered in the "outgoing" portion of the network and must be taken into account.

(5) LED from central office switch to distribution repeater detector.

(a) LED output light power:	0 dB
(b) Coupler loss (LED to switch)	-7 dB
(c) Central office (outgoing stages)	
2 stage at 1 dB/stage loss:	-2 dB
Optical interconnections loss:	-2 dB
(d) Coupler loss (switch to fiber):	-7 dB
(e) Fiber loss at 1 km:	-14 dB
(f) Coupler loss (fiber to detector):	-7 dB
(g) Received signal power at detector:	-39 dBm

Only those local subscribers served outside a 1-km route distance from the central office are in need of distribution repeaters. Because the utilization[22] of lines is approximately 0.1, fewer repeaters are needed at the central office than the total number of subscriber lines entering that central office. There are a few subscriber-to-subscriber calls that require no repeaters.

(6) Local subscribers not requiring repeaters at central office.

(a) LED output:	0 dBm
(b) Coupler loss (LED to fiber):	-7 dB
(c) Fiber loss 0.214 km:	-3 dB
(d) Coupler loss (fiber to switch):	-7 dB
(e) Central Office Switch (incoming)	
2 stage at 1 dB/stage:	-2 dB
Optical interconnections loss:	-2 dB
Central Office Switch (outgoing)	
2 stage at 1 dB/stage:	-2 dB
Optical interconnections loss:	-2 dB
(f) Coupler loss (switch to fiber):	-7 dB
(g) Fiber loss 0.214 km:	-3 dB
(h) Coupler loss (fiber to detector):	-7 dB
(i) Received signal power:	-42 dBm

This indicates that any local calls originating and terminating within a two-way route distance of 428 meters do not require central office repeaters.

3.2 Trunking System

Light sources assumed for this system are stabilized[19,23] mode-locked lasers oscillating at 504 Mb/s. The output pulse train from the laser is split into several dozen lower powered "copies", each separately modulated and coupled to a single mode fiber. Output pulses are assumed to be modulated by Pockels-type $KD^{+}P$ crystals. Summarized below are the characteristics of the system.

(1) Laser

Output light power:	5	watts ave.
Wave length:	1.06	μm
Pulse width:	50	ps
Pulse period:	1.98	ns
Duty factor:	0.0252	
Watts per pulse:	198	
Output light power per pulse:	+33	dBm

(2) Beam Splitter (128 outputs)

0.1 dB/prism	
3 dB/split	
7-stage binary	
Loss at each output:	-21.7 dB

(3) Modulator

1/2 wave voltage:	35 volts
Contrast:	25.1
Maximum modulating frequency:	252 MHz
Insertion loss:	-3 dB

(4) Coupler loss (modulator to fiber): -7 dB

(5) Fiber from Modulator Coupler to Detector Coupler

Single mode (1-μm diameter $\lambda = 1.06 \mu$m)	
Unit loss:	14 dB/km
Length:	4 km
Loss:	-56 dB

(6) Coupler loss (fiber to detector): - 7 dB

(7) Detector: Silicon Avalanche Photo Diode[18]

Received signal power:	-61.7 dBm
Detector bandwidth:	300 MHz
Signal-to-noise ratio:	20 dB

Received signal power per pulse is 5 dB above the lower limit reported.[18] The pulse signals are received, detected, retimed, and applied to modulators of a similar type as described above. The trunk losses between offices can be recovered by repeatering using the same scheme (that is, with laser, beam splitter, modulators, couplers and fibers).

4. SUMMARY

The use of LED's in the local distribution plant, and mode locked lasers in the trunk plant is the uniqueness of the system approach studied here. Multimode fibers in the distribution plant and single mode fibers in the trunk plant go hand-in-hand with this approach. Pulsed transmission is used throughout.

Devices needed in the optical communications system fall mainly into two classes: optical and electronic. Today they are highly specialized and not yet subject to economies of scale. A prediction that a price reduction from today's off-the-shelf prices for the specialized equipment is as follows:

Optical equipment prices will drop to 1/10 of today's prices by 1985.

Electronic equipment prices will drop to 1/5 of today's prices by 1985.

This is based on expected technological improvements resulting in manufacturing simplification, hence cost reduction. Significant improvements in the reliability of critical components are required before a practical system for commercial use could be installed.

Switching requires that certain communications lines be repeatered; therefore, light sources (lasers), modulators, detectors, and multiplexers will be needed. All outgoing trunks and only those lines served outside a 1-km route distance from the LDC are in need of repeaters. Because the utilization of lines is approximately 0.1 and trunks is 0.7,[22] fewer repeaters are required than this. By pooling repeaters in the switching center, they can be switched into lines and trunks needing them.

Central office repeaters are required, and the estimated number can be determined from traffic considerations. If it is assumed that 60 percent of the subscribers would be served simultaneously, then the number of central office repeaters required would be 0.3 x the number of subscribers. The number of ports on the switching array is 1.15 x the number of subscriber main stations to account for incoming and outgoing trunks to other offices; and to provide for operator and maintenance positions.

Distribution repeaters can serve up to 100 subscribers; however, only subscribers outside the 1-km route distance limit require repeaters.

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Dr. Fulenwider is a member of Eta Kappa Nu and Sigma Xi.

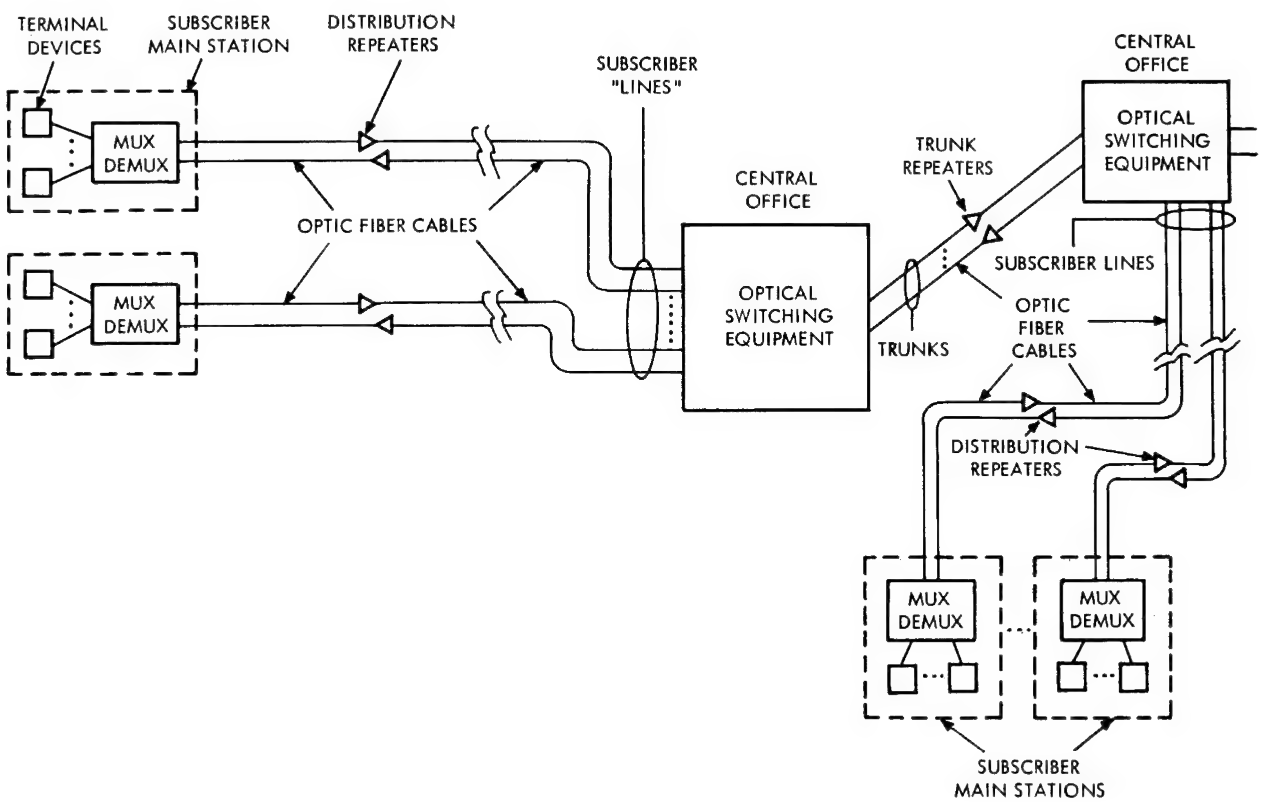

Figure 1. Optical Communications System Functional Layout

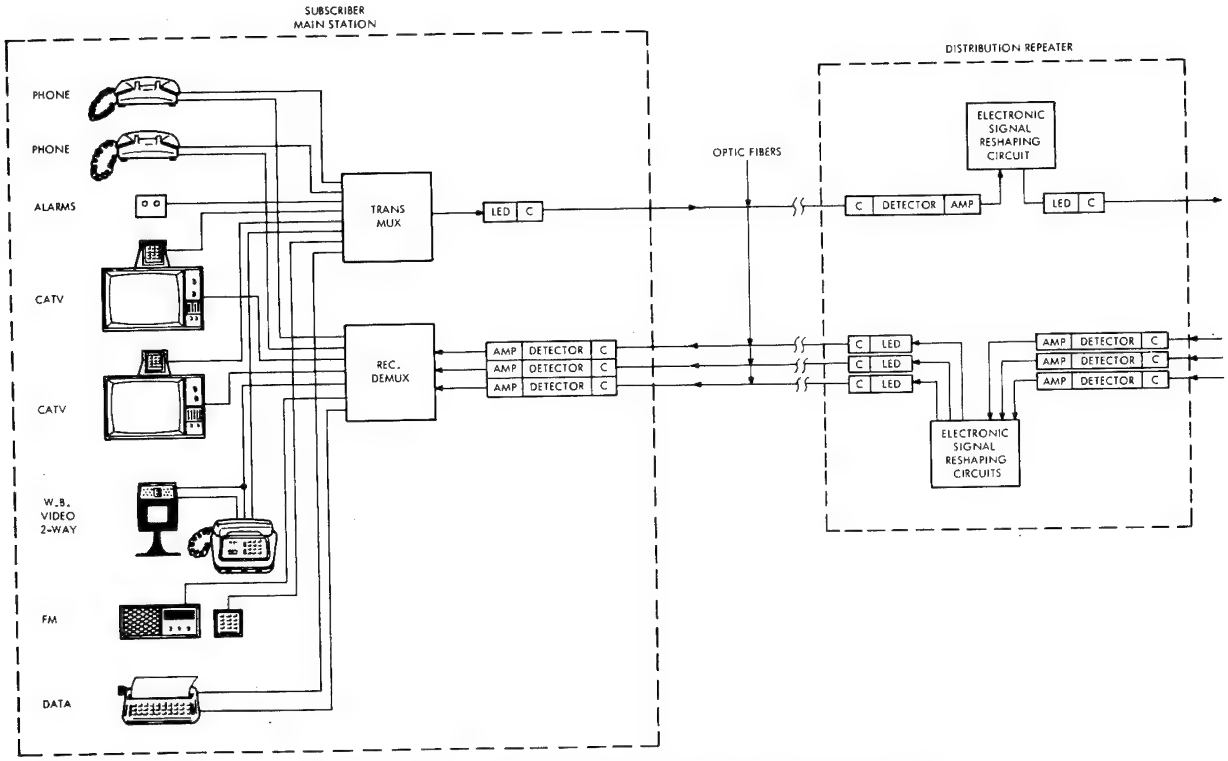

Figure 2. Distribution "Loop" Using Light-Emitting Diodes and Multimode Fibers

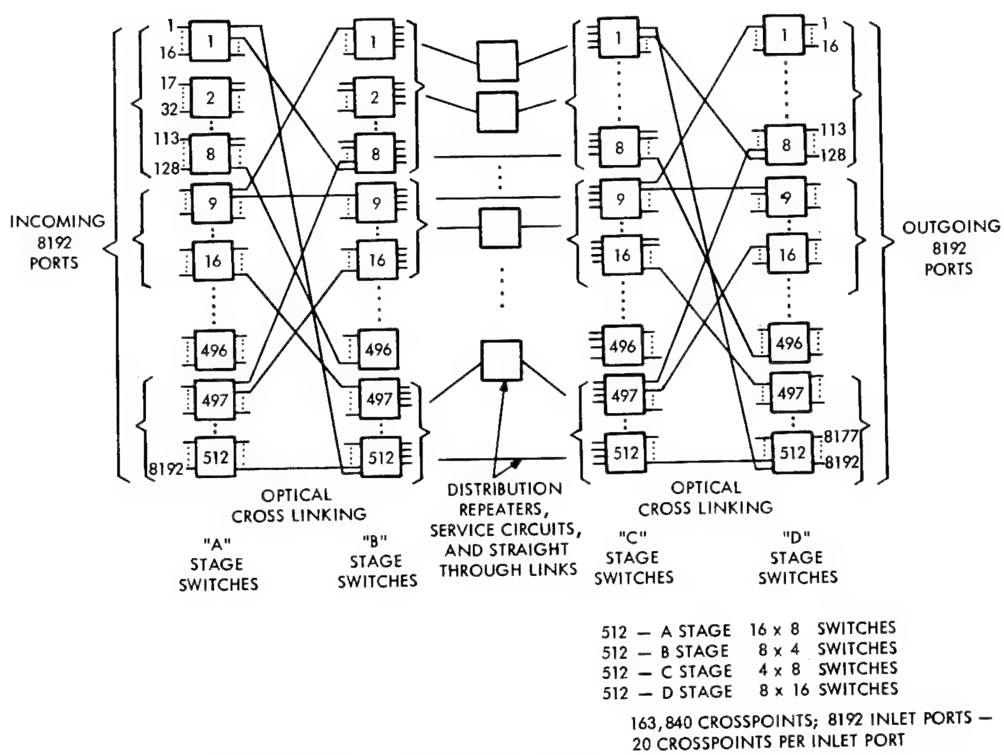

Figure 3. Four-Stage Switching Array for Typical 8192-Port Space-Division Switch for Conveying Pulsed Optical Signals

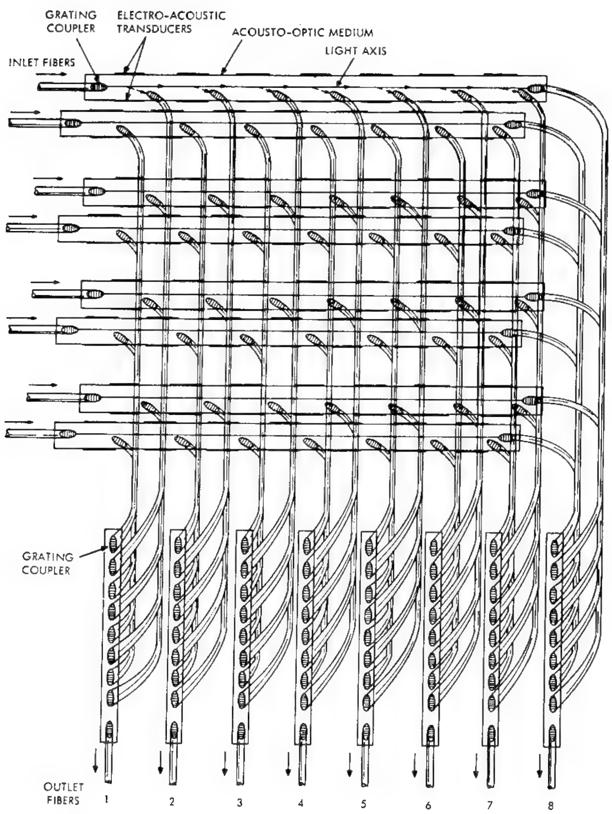

Figure 4. Suggested Form of 8 x 8 Optical Crosspoint Switch

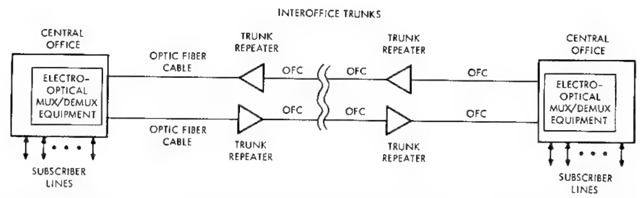

Figure 5. Interoffice Trunking Using Optic Fiber Cables and Repeaters

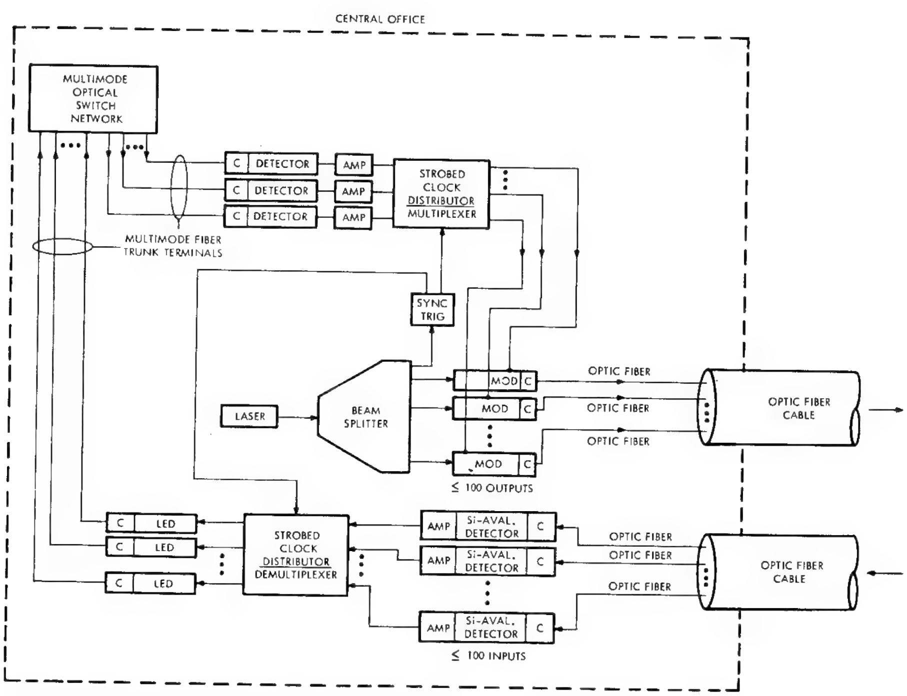

Figure 6. Electro-Optical Multiplex and Demultiplex Equipment

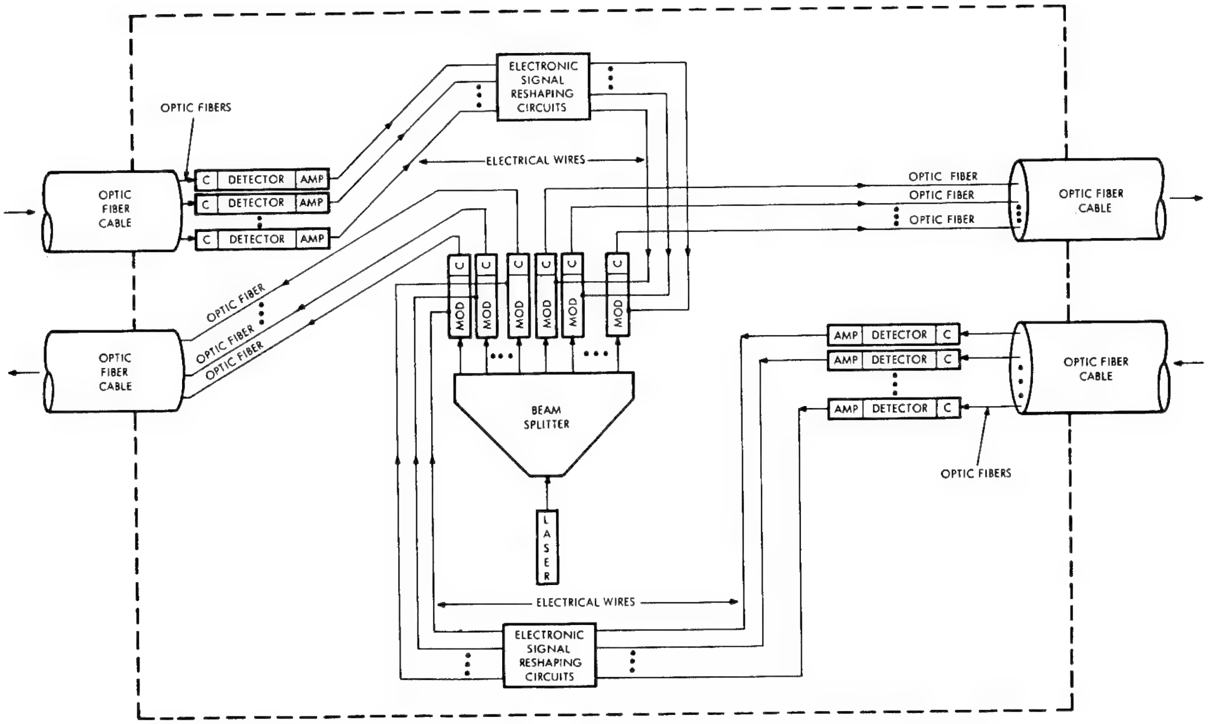

Figure 7. Electro-Optical Trunk Repeater Station

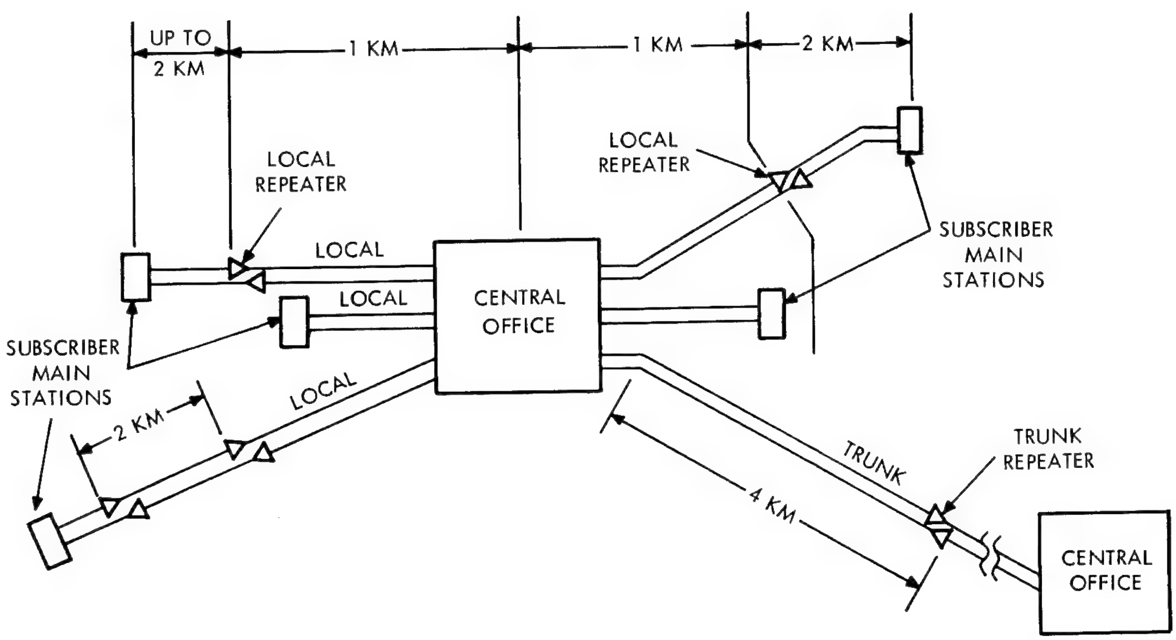

Figure 8. System Plan for Switched Optical Communications

PROBLEMS OF WATER IN PIC CABLE

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ABSTRACT

Water in PIC cable has caused such problems as shield corrosion, conductor erosion, noise, transmission irregularities, telephone service outages, impairment of analog transmission and total blockage of pulse code modulated transmission. The present challenge is to prevent future water entry and to economically restore existing wet cable to acceptable performance.

INTRODUCTION

Scope of Paper

This paper describes some of the actual problems of water in PIC (polyethylene insulated conductor) cable encountered by the General Telephone Company of Illinois since 1959. Since the telephone maintenance forces are primarily responsible for prompt maintenance and restoral of service, that part of plant causing the problem may be and has often been replaced and disposed of before a design engineer is on the scene to thoroughly examine, test and document all conditions. Field conditions seldom permit the preciseness of laboratory instrumentation necessary for design work. The summary will show that some problems have been overcome, but many still exist.

While this discussion will focus primarily on the problems caused by the water and the need for corrective and preventable action, some background information is desirable. Because of the wide variety of environmental conditions encountered by PIC cable, we will attempt to keep the discussion as general as practicable and review specific examples to show what has happened.

Hopefully, the sharing of this experience and the conclusions reached will be helpful to other users as they make their decisions and will challenge the manufacturers to develop economical methods to overcome the problems encountered. No credit is taken for methods developed by others and the use of proprietary names has been avoided in this presentation.

Progressive Cable Development

Prior to the later part of the 1940's the standard type of telephone cable used in outside plant was composed of paper-insulated copper conductor pairs enclosed in a lead sheath. This type of cable provided good service under most environmental conditions with predominantly aerial type of construction. When used for underground construction, the lead sheath cable was found subject to sheath damage from corrosion varying from minor to severe, depending upon soil conditions and stray ground currents. Nonconductive outer coverings such as jute or neoprene and cathodic or forced electrical measures were used to mitigate this problem. Shortly after World War II, composite sheaths for telephone cable were introduced as a replacement for lead which was in short supply. The early composite sheaths, such as Alpeth applied over paper-insulated pairs, did not provide sufficient moisture resistance and could not be hermetically sealed at splices. As a result, poor insulation due to moisture in the paper-insulated core was a serious problem. About 1951 Stalpeth sheath was developed for use as a jacket over paper-insulated cable. This sheath design consists of a corrugated and folded 8 mil aluminum tape applied with an open gap, a 6 mil tin coated steel tape corrugated and folded with the overlapped seam soldered, an asphaltic base flooding compound applied for corrosion protection with an overall cover of polyethylene. Stalpeth sheath is now utilized on virtually all paper-insulated telephone cables.

About 1950 the first polyethylene-insulated telephone cables were introduced. There was a general opinion at that time that the moisture resistance of polyethylene insulation would eliminate the need for a moisture-impervious overall sheath and would have many advantages over the types of cable previously used. This PIC air-core cable was more economical, easier to place, simpler to splice, lighter and apparently did not require the hermetic seals needed for paper-insulated cables. Initially the new cable was installed predominantly in aerial construction. However in the middle 1950's improved direct burial methods were developed using both trenching and plowing techniques and direct cable burial in the soil gained wide acceptance. Advantages of buried plant when compared with convential aerial plant

usually include lower first cost, fewer service interruptions from natural causes, elimination of the need for tree trimming, faster construction and aesthetic appeal. The trend toward buried construction has been further accelerated by the continued development of more efficient economical plowing techniques and above-ground pedestals which provide easily accessible locations for splicing, distribution, and testing purposes.

The use of PIC air-core cable originally worked well for Plain Old Telephone Service (POTS). Analog carrier was applied to these cables with apparent success. As more experience was gained with buried cable installations, it became evident that the outer jacket of PIC cables was vulnerable to hazards such as damage during installation, rodent attack, digging damage and punctures by lightning-induced surges. About 1960 serious deterioration was found in the aluminum shield at points where the shield was exposed to water. With the exception of cases where objectionable induced noise resulted from loss of shield continuity, the POTS customer seldom noticed the progressive change in transmission qualities when water began to accumulate in the cable.

Some users specified an inner polyethylene jacket for direct burial cables to provide an additional moisture barrier and higher dielectric strength between the shield and the core. However, this inner jacket offered no additional protection to the aluminum shield and progressive corrosion occurred as long as moisture was present. The use of a copper shield in place of aluminum was applied in some cable designs to retard corrosion.

As a further refinement, FPA (fused polyethylene aluminum) shield was developed to retard the rate of shield corrosion.[1] It was still assumed that some moisture or water in the core could be tolerated for POTS. Successful operation of large quantities of PIC cable with FPA shields since 1963 has confirmed the effectiveness of the new shield in controlling corrosion.

Additional cable developments include CCW (continuous corrugated and welded-seam cable) using 16 or 20 mil steel, gopher-proof cable using 6 mil corrugated steel with overlap and a vapor-impervious core envelope consisting of a strip of aluminum foil 0.7 mil thick, coated on both sides with a polyethylene copolymer film and with the joining edges heat sealed.

Experience gained over a period of years has exploded the original assumption that a certain amount of moisture or even a limited amount of solid water could be tolerated within the core of a plastic-insulated cable. It was a known fact that the presence of water in the core increases the mutual capacitance component of pair impedance with adverse effects on transmission characteristics at both voice and carrier frequencies.[2] It has originally been assumed that the plastic insulation and sheath material would be practically impervious to water, but in practice it was found that there are small pinholes which occur in the plastic insulation during manufacture and apparently cannot be avoided. It was also found that water, after gaining entry through a sheath defect, would flow freely through the plastic-insulated core and would accumulate at a point other than that of entry without being checked by swelling of the insulating material as is the case with paper-insulated cores. This condition produced a situation where solid water would accumulate at low spots in the cable resulting in severe localized impedance irregularities.

A later development intended to prevent moisture and water problems uses a cable core consisting of polypropylene-insulated conductors which is filled completely with a compound consisting of petroleum jelly and polyethylene jelly using a modified alpeth sheath.[3] We understand that this cable is designed to have the same essential electrical characteristics as standard telephone cables below 500kHz to minimize impedance irregularities when both new jelly filled and existing air core sections must be utilized in the same route. There is approximately a 13 percent reduction in attenuation and a 10 percent reduction in impedance above 500kHz in jelly filled cable when compared to standard air core cable.

Operating Environment

PIC cables are used generally for both indoor and outdoor plant facilities. Inside plant includes cables used for distribution systems in office buildings, hospitals, apartment complexes, and other locations where there is concentrated demand for telephone service. Normally, these indoor applications enjoy very favorable environments. This discussion is limited to outside plant where the cable is exposed to moisture and other environmental problems.

The outside plant cables may be buried, placed in underground conduit, or used in aerial construction. With today's service requirements and state of the art, any cable installation may be called upon to meet the requirements of voice frequency message or special service circuits, analog carrier, and PCM carrier. This requirement applies to both exchange and interexchange cable facilities. Applied voltages range from 48 volts to above 300 volts under present techniques.

Aerial PIC cables are subject to potential hazards of wind, sleet, ice, rain, sunlight, falling or moving objects, and atmospheric conditions which may cause contamination. The wide use of ready-access terminals for aerial distribution and splicing allow moisture ingress points even when no sheath damage exists. Any moisture or water intake then seeks and concentrates at the low points in locations adjacent to the point of entry.

Although direct buried cable generally has the advantage of installation ease, aesthetic factors and protection from many natural or man-made casualties, it is not without problems. The environment of direct buried cable can vary from swamps and soft soil to rocks and cinder beds. Once in-

stalled, the buried cable is subject to attack by rodents, and damage from lightning and digging operations. Repair of buried cable is more difficult than aerial or underground cable.

When considering the placing of buried cable it is important to recognize that it is not feasible to make integrity inspection after installation. Therefore, positive control of the laying operations to avoid cable damage and maintain sheath integrity is essential. Although there has been continuing refinement in placing equipment and techniques, many sheath faults have been traced back to installation damage. Splicing methods for underground and buried PIC cables have evolved progressively, but there is still room for considerable improvement.

Need For Reliability and Continuity of Service

Historically telephone companies have recognized the necessity for reliability and continuity of service as is evidenced by the installation of redundant ringing machines, batteries for power supplemented by emergency power plants and the continuing change to subsurface cable plant. In order to meet customer requirements and demand, it has been necessary to use facilities more sophisticated than hard wire. Service is no longer limited to slow-speed dial pulses and communication in the voice range, but now includes frequency band width requirements from DC to 1.5 mHz and data speeds up to 1.54 megabits per second. Further increases in band width and speed requirements can logically be anticipated. Since data transmission is non-redundant and service demands for computer-to-computer communications require minimum human intervention, minor service interruptions or impairments which were of little consequence for POTS are now intolerable. Since service reliability is a prime consideration, neither poor quality nor outage of communication services is acceptable.

Experience now shows that the presence of water in telephone cables, regardless of the type of insulation used, constitutes a serious threat to both present and future communication service. The present trend from analog to digital carrier systems is necessary to meet the rapidly expanding demand for data transmission. These digital carrier systems impose much more stringent operational requirements on cables through which they are routed than is the case for analog carrier and voice frequency systems. Some method must be developed to overcome or prevent the moisture and water problems in both existing cables and those to be provided in the future.

PROBLEMS CAUSED BY WATER IN PIC CABLE

General

The problems attributed to water in PIC cable are difficult to quantify as the many variables are interrelated, single fault assumptions are not valid, and there are no clear-cut boundaries of both cause and effect. The problems are detected by customer complaints, service outages or routine testing. Although this paper directs attention to noise, transmission deterioration, and corrosion, it is recognized these areas overlap and there is some repetition in the presentation. Another major problem is the economic penalty incurred when plans, based on continued or expanded use of existing cables, must be changed because the cables are found unsatisfactory for the application originally planned.

Basically, the electrical characteristics of a facility are determined by the physical arrangement and composition of materials such as conductors, insulation, dielectrics, etc. Water entry changes these physical arrangements by displacing the air dielectric with water and providing a path for current flow through pinholes in the conductor insulation. Changing the dielectric, changes the capacitance. The current flow can erode the conductor to failure. At all stages of change the transmission is affected. Over the years, cable has been replaced because of noise and corrosion, especially the non FPA type. Perhaps the most traumatic shock was the failure in our first attempt to turn up a PCM carrier system on an existing cable that passed standard transmission tests with the subsequent discovery that there was water in the cable and that water was the cause. The following examples will illustrate experiences in these areas.

Noise

Noise is one of the parameters that all communications engineers must recognize and determine how to control. GTI experience reveals that the usual first indication of water in exchange cables used for POTS is customer complaints of objectionable line noise. The noise caused by current flow through the pinholes is considered a progressive fault. The fault may be temporary or permanent depending upon when it is detected and how it is corrected. This noise may involve one or more cable pairs. The initial action to satisfy customer complaints is usually to transfer the working circuit or circuits to other cable pairs which operate satisfactorily. This transfer does not eliminate the cause of the difficulty, but satisfies only the customer's immediate problem. Because some of the pairs in the cable are still operating, the cable failure is partial in this point in time rather than total. As cable deterioration progresses, more and more pairs become unsatisfactory until a point is reached where cable replacement becomes the only solution. A similar pattern exists on interexchange cables. At present, GTI has found no satisfactory corrective measures other than replacement of involved cable sections, even when water trouble is detected at an early stage. However, a method discussed later involving the injection of a displacing substance may provide a solution to the problem, when the problem is detected before major structural damage occurs.

Transmission Deterioration

The provision of satisfactory local and nationwide toll message service, together with meeting requirements for special service facilities, is dependent on maintaining satisfactory and stable network transmission parameters. Since these parameters depend on the characteristics of all the facilities used, the effects of water in cables can extend far beyond the local exchange area immediately involved. Before physical deterioration of the cable takes place the effects of water on electrical characteristics become serious.[2] As water displaces the air in the PIC cable core, the increase in the dielectric constant produces a change in the impedance characteristics of the cable pairs. The resulting reduction in return loss at voice frequencies impairs the operation of gain devices, such as amplifiers, and can result in disabling oscillation on built-up switched connections. A prelude to this final condition is often observed as hollowness or echo on working voice frequency circuits. The changes in loss and slope characteristics also seriously impair successful operation of a wide variety of special service circuits which may be assigned to voice frequency facilities. For example, while making routine toll office terminal balance tests, serious transmission irregularities were found on a trunk cable used for voice frequency facilities. Investigation disclosed extensive water accumulations and replacement of the wet sections was required.

At carrier frequencies, the presence of water in the cable core becomes even more serious. The displacement of air in the cable core with water approximately doubles the mutual capacitance of the pairs in the sections involved. This change affects the impedance and loss characteristics of the pairs with resulting displacement of the frequency response curve and distortion of its shape. The result is an unpredictable variation in performance, which appears to be some function of the lengths and locations of wet cable sections.

With carrier systems, repeater sections along cable routes are designed at optimum spacing, considering both economic and performance factors. The entrance of water in the cable ultimately produces noise and distortion on some or all channels of the analog carrier systems. On analog systems corrective readjustments of repeater gains, slopes and levels are, at best, only a temporary means of restoring service and in many cases this measure is not feasible because of the necessity for coordinated levels between systems within the cable and at cable junction points. Attentuation distortion of an analog carrier system will begin with the initial ingress of water into the cable core and will grow progressively worse as the water accumulation increases. The effects will be progressive increases in noise and distortion together with cross coupling between carrier systems, increasing difficulty in maintaining proper alignment of the carrier systems, the loss of some channels, and eventually complete service failure. Unless early measures, as discussed later, are taken to correct and prevent water intake, the replacement of either sections or all of the cable becomes necessary.

In the application of pulse-code modulated (PCM) cable carrier systems the presence of water-filled sections of cable core may cause the systems to be unworkable. With the bit stream rate of approximately 1.5 megabits per second employed for T-1 Type PCM carrier systems, even relatively small water pockets can totally disrupt system operation when fixed line build out repeaters are used. Some correlation has been observed between the relative locations of repeater points and wet cable sections in the degree of operational impairment of PCM carrier systems. A degree of operational latitude can be secured by using automatic regulating repeaters but experience to date indicates that PCM carrier should never be applied on a cable which shows evidence of water intake or accumulation. This reliability risk tends to preclude the use of PCM carrier on existing air-core PIC cables unless they are dry and some satisfactory method can be developed to prevent future water ingress. A recent example follows which illustrates some of the problems encountered.

> In this case, T-1 Type PCM carrier was applied on approximately 13 miles of existing air-core PIC cable which was apparently in satisfactory operating condition. Normal tests, including attenuation and cross coupling at frequencies up to 722kHz failed to disclose any meaningful irregularities. The initial attempt to turn up the PCM carrier system was unsuccessful. After very extensive tests, including those with a repeater test set, a suspect section of the cable was determined. The suspect section of approximately 300' length was then bypassed with a new temporary cable, after which the carrier system worked satisfactorily. Subsequent inspection of the bypassed section disclosed short sections of the cable core filled with water at low points in the cable run.

This experience showed that standard transmission tests for cable were not adequate for PCM carrier application as they did not detect the presence of water. Some test was needed for maximum distinquishability of the existence of water in the cable.

Since that event, GTI has used instruments working on reflection principles and have found that they will accurately locate water pockets in PIC cable cores. Present procedures are to thoroughly test all existing and new cables with the reflection type set before engineering and applying PCM carrier systems. A substantial portion of existing air-core cables tested for PCM carrier application have been found to have serious water problems. In these cases, a judgment decision on whether or not to apply PCM carrier, after clearing known water situations, involves considering the risk of future service failure due to water intake at other locations.

Corrosion

As previously stated, the presence of water or moisture in PIC cables carrying direct current potentials produces corrosion or erosion which directly affects the structural integrity of the facilities used for transmission of electrical signals or intelligence. With the present trends toward use of finer-gauge conductors and higher applied electrical potentials, the problem becomes increasingly acute since these factors accelerate destructive corrosion and increase the speed of service deterioration.

> In 1971 an air core PIC cable installation was made using 24-gauge cable with loop extenders which applied a total of 96 volts to a number of pairs. Water entered portions of this cable through sheath faults and rapid deterioration was detected in 1972. Inspection at fault locations disclosed that some of the conductors were eroded by electrolytic action and that insulation damage existed on these pairs.

An assumption was made that when the conductor insulation faults exposed the conductor to moisture or water, the resulting corrosion progressively reduced the conductor cross section with a corresponding increase in resistance and heat generation. Because of the extremely limited heat dissipation in the core, progressive acceleration of the destruction cycle occurs. Our experience shows many cable installations involving 48 volt applications performed satisfactorily for several years before the first evidence of trouble was observed. However, after deterioration began, usually involving a relatively small number of cable conductors, the rate of deterioration progressively increased, resulting in an early need for total replacement. The rate of corrosion damage appears to be correlated with the gauge of cable conductors, the applied voltage, and the length of time that moisture is present.

> In another situation, a buried 900 pair 26 gauge PIC air core cable 983 feet in length and approximately 2½ years old was involved. Normal 48 volt battery was used on the POTS lines routed through the cable. Customer complaints of line noise, together with development of open pairs led to investigation and an attempt to restore the cable to serviceable condition. Initial measures for service restoration had been the usual change of involved services from the defective pairs to previously unused pairs which were in good condition. Continuing development of trouble showed that either some means must be taken to prevent further deterioration or the entire section must be replaced. Tests with a reflection type meter determined that there was water in a section of the cable. An attempt was made to salvage the cable by displacing the water with a material which remains in and fills the cable core. Subsequent tests on the involved pairs showed acceptable leakage and noise levels, but several pairs became open during the injection process. Some additional open pairs developed during the first month after the treatment of the cable. It is deduced that it was not the properties of the compound but the mechanical disturbance of eroded conductors during the injection process that caused conductor breakage or cracking which resulted in both immediate and early subsequent failure. Later reports indicate very few pair failures after the initial reports. Present indications are that approximately 90 percent of the pairs in the 900 pair cable have been salvaged. Since there is no practical way to examine the condition of the pairs without dig-up, it is assumed they will continue to perform satisfactorily. Time will tell.

In the two preceding examples the problems are attributed to pinholes in conductor insulation resulting in conductor erosion as well as immediate service impairment on the circuits directly involved. Electronic telephone switching promises economy in outside plant by enabling the use of longer electrical loops utilizing finer-gauge conductors, but it can be concluded that present water problems in cables pose a serious threat to these potential economies.

General conclusions are that water cannot be tolerated for long periods of time in PIC cable regardless of the use. The length of time before service difficulties occur depends on each specific application but the end results can be the same, total failure requiring cable replacement.

Economic Factors

Cables are selected and placed by GTI based on the results of economic selection studies. Many of the existing rural and interexchange cables are planned and sized to provide hard wire facilities for the projected circuit requirements up to a certain point in time with the application of carrier for the circuit growth in the later years of the study period. Both analog and PCM carrier systems are used for interexchange circuits and subscriber growth and upgrade. Water is being found in many of these cables which precludes the use of carrier until portions of the cables are either replaced or the water is removed. These economic penalties may be overcome if a proven economical method to salvage these cables becomes available. Under present salvage or water removal techniques that are discussed later, it is less costly to replace the smaller size cables than to reclaim them.

POSSIBLE CAUSES OF WATER IN PIC CABLE

Occasionally, but not often, water is found in PIC cable when it is received from the supplier. It can seldom be determined how or where the water intake occurred, but it is reasonable to consider the possibilities of entry during manufacturing, shipping, and storage.

Water used for the cooling processes during

cable manufacture is a possible source, but it must be assumed that the manufacturer takes all reasonable precautions to prevent water from being retained in the cable core, since he is vitally interested in producing a quality product. Entry of water into PIC cable may occur during shipment of the cable from the factory or storage area to the installation site. The use of end seals and the maintenance of air or gas pressure during the handling and storage processes is desirable to prevent water entry and monitor sheath integrity. Rough or improper handling can be a cause of undetected sheath damage resulting in future service problems.

The environmental conditions of the user's cable storage area often leave much to be desired. High humidity and wide temperature variations are not unusual. Damage due to accidents or vandalism has occurred. Failure to replace end seals after removal for checking gauge and number of pairs has been found to be a cause of water problems during storage. Failure to place end seals on the unused portion of cable returned to the storage area has also been found to be a cause of water-intake problems.

Many cable faults have been traced back to damage during installation. One extremely frustrating aspect of placing buried cable is the absence of any practicable way to inspect for sheath faults immediately after placement. After the cable passes through the plow or is covered in a trench visual inspection becomes impossible except by dig-up procedures. This limitation imposes rigid operational quality controls on the plowing or laying procedures.

The development and refinement of construction methods, together with adequate training and indoctrination of installation personnel has been a challenge since buried cable construction began. Considerable improvement has been made. Common causes of sheath damage during installation, such as stretching of the cable, have been improper design, improper usage and inadequate maintenance of installation equipment. With skilled workmen, this problem can be practically eliminated as there has been continuous development in the quality and efficiency of machinery used in cable burial.

Water entry into the cable after installation is a serious problem even if no sheath faults exist. Known cases of water intake include those where pedestals have been flooded by high water. In most cases such conditions are the result of poor judgment in specified pedestal locations or actual installations and could have been avoided. Condensate forming within pedestals not subject to flooding presents another possible source of moisture or water intake but its relative contribution to the total water problem is unknown to us. Sealing the cable ends at pedestals will prevent water entry at this source but will increase the installation cost.

Another possible source of water in air core PIC cable is "pumped" permeation through the plastic sheath in combination with temperature cycling. Experimental and analytical work on this subject indicates that, with a single sheath polyethylene air core cable, quantities in the range of one gram of water per foot of cable per 30 years may accumulate with a daily temperature cycle of ± 1 degree Centigrade and an external humidity of 100 percent.[4]

Permeation is not considered a problem.

After it is placed, buried cable becomes subject to both sheath and core damage from manmade causes which may involve construction or farming activities. Such causes may not be reported by the persons causing the damage due to fear of possible liability for repair cost and legal involvement. In some work operations, such as sign placement, heavy excavation and hauling or deep tillage, the operator of the equipment may rupture the sheath when it is unexposed and not realize that he has caused cable damage. In these cases, there may be no indication of damage until circuit failure occurs.

Lightning strokes very often produce sheath and insulation punctures at points remote from the immediate point of entry.[5] These remote damage points may vary in distance from a few feet to, in abnormal conditions, a mile or more depending on earth conductivity conditions, adequacy of shield bonding and proximity of low-impedance ground points. It is not uncommon for lightning to produce both sheath and conductor insulation punctures at multiple locations in both directions from the initial damage. Repair of damage at the immediate location may be followed after months or years by failure at remote points. In buried PIC cables, we know of no practical way to determine the existence and locations of all secondary damage points.

Sheath damage due to gnawing of rodents such as gophers, squirrels, rats, and mice is a very serious problem in some areas since water entry points can result. At the present time steel-armored cables are extensively used to minimize gopher damage.

POSSIBLE SOLUTIONS TO WATER PROBLEMS IN EXISTING PIC CABLES

When water is found in an existing cable, one must determine the extent of the problem, and how to solve the problem. Consideration must be given to the present and future use expected of the cable; the source of water entry; the probability of future water entry in the sections not presently in trouble; the probability of water reentry in the section being repaired or replaced; and the type of cable to use for replacement, in addition to the estimated present and future cost. The size of the cable is a major factor to consider when evaluating the cost of repair versus replacement. It may be both difficult and expensive to locate and repair all water entry points. Water may flow through the core and collect at low points considerably removed from the point of entry. To our knowledge, no pos-

itive means except dig-up has been developed for the final location and repair of sheath faults in buried cable. Where PCM carrier is to be used, total replacement may be advisable. Usually voice circuits and analog carrier give a warning of water problems by noise and cross talk before total failure. PCM carrier will fail with no warning when water or other irregularities cause errors in the order of 1 error in 10^5 bits. Development of some practical and economical method for early detection and location of moisture entry on existing air core PIC cables would provide a valuable aid in maintaining service on existing cables.

The following three methods for dealing with water problems in existing cable have all been used with some degree of success:

1. Replace the cable.
2. Purge, dry, and repair the cable.
3. Displace the water and air with a material which will fill and remain in the cable core.

Replacing the cable may consist of replacing the entire cable or only the damaged sections. In the past, GTI has replaced only the damaged section or sections with air core PIC cable after attempting to determine and eliminate the cause of water entry. Future replacements are expected to be with filled cable.

Over the years, some users have tried to displace the water by various means, dry the cable, and repair the damage at the points of entry. In the early 1960's, we witnessed a demonstration of displacing water and moisture from the cable core by the insertion of fluids such as acetone which will absorb water, followed by purging of the fluid from the cable by nitrogen gas under pressure, leaving the air core dry and the electrical characteristics essentially unchanged.[6] More recent developments use the same method but incorporate compounds to absorb and purge the water, leaving behind a residue which is intended to seal insulation pinholes and minor sheath openings. In either case, the remaining sheath breaks must also be repaired. In evaluating the purge, dry and repair method, consideration must be given to possible safety hazards, the cost, and the probability of future water reentry. We do not use this method because of the hazards involved.

Another method has recently been developed by Bell Laboratories for removing water.[7] This method consists of displacing both the water and air from the PIC cable core with a material which is injected under pressure and is intended to remain as a jelly in the core to form a complete filling, thereby excluding future water entry. This method shows promise and further refinements in methods and materials seem warranted.

ALTERNATIVES FOR NEW CABLE INSTALLATIONS

The alternatives are based on the premise that the required facilities will be provided by PIC cable. The reliability of the final installed facility depends upon the overall planning, the quality and condition of the materials used, the environmental conditions present and the craftsmanship of the workmen.

The following three alternatives are methods of providing PIC cable facilities but only one will prevent water entry:

1. Continue with air core PIC cable.
2. Continue with air core PIC cable and maintain the cable under gas pressure.
3. Use filled core PIC cable.

The first alternative is to use the present air core PIC cable and expect that all reasonable measures will be taken to provide a good quality installation and initial sheath integrity. Experience tells us it is unwise to continue using the present "state of the art" air core PIC cable and expect to meet service requirements of the future, yet, it is an alternative and meets some of today's requirements under certain conditions. If this alternative is chosen, full consideration and recognition must be given to the risks involved; the potential limitations of use, the problems caused by water entry at initial and future sheath openings, and the associated repair costs.

The second alternative is only a possible refinement of the first. The true value of pressurization of PIC cables is very questionable and difficult to quantify. The pressure system will indicate initial sheath integrity and may help to detect and locate sheath breaks soon after they occur if adequate alarm contactors are provided. GTI has no evidence that pressure prevents moisture entry into PIC cables. Because of the rapid propagation speed of gas in an unfilled PIC cable core, the use of pressure sensitive contactors serves only to sectionalize the location of a sheath fault. Some other method is required for precise fault locations.

The third alternative of using filled core PIC cables appears to be the most practical method now available to prevent water entry and avoid the associated problems. Hopefully, the premium in first cost will be justified by reduced maintenance cost, more reliable service, and longer facility life. Compared with air core cable, the filled cable is heavier and more difficult to handle and splice. Further refinement in placing, splicing and terminating techniques are desirable and can logically be expected. Based on past experience, some presently unforeseen problems can be expected but these should not be insurmountable.

SUMMARY

While we have reviewed the background and stressed the need for economical, reliable service, the focus is on the problem - the cause and effect- and possible action for the future. Although an accurate statistical analysis of these problems was not possible with existing data, we feel the following points are worthy of consideration by the users and manufacturers.

1. Water does enter air core PIC cable and causes physical deterioration of both the shield and the conductors where the metal is exposed to the moisture.

2. Water enters air core PIC cable through unsealed cable ends at terminals or pedestals and through sheath faults caused by installation casualties, lightning strokes, rodents and man-made damage.

3. Water in air core PIC cable causes localized changes in electrical characteristics with resulting noise, transmission irregularities, and service failures on both voice frequency and carrier circuits or systems.

4. Physical deterioration of cable pairs in use is progressive and permanent. Failure of voice frequency circuits and analog carrier circuits is considered progressive, but failure of PCM circuits is considered abrupt or catastrophic.

5. Reflective type test equipment will determine the location of water accumulation but does not necessarily identify the actual point or points of water entry.

6. A safe and economical method for purging water from air core PIC cable with full recovery of the use of all pairs is not yet available. However, considerable promise of success appears in the method of purging the cable with a compound which expels both air and water and remains to fill the core. Early detection and treatment is essential.

7. In view of the necessity for long service life of cable plant, the increasing demands of present and future electronic equipment, and the necessity for reliable service, water must be excluded from cable cores. On new installations, the use of jelly filled PIC cables appears the most practical way of meeting this need.

DISCUSSION

General Telephone of Illinois has installed over the years approximately 28,000 sheath miles of PIC air core cable. Approximately 80 percent of it is 19 and 22 gauge. The remainder is 26 and 24 gauge. In most cases, the cable has and is providing satisfactory voice frequency hard wire telephone service. We suspect there are water pockets in much of it. Experience shows rapid conductor deterioration of the finer gauge cables where moisture is present and especially where higher voltages are used. Although we have been unable to quantify in the field the statistical relationship of gauge, voltage, time, and moisture to predict either failure rates or service life, we know the relationship exists. Were we not concerned with economies and service demands that require present and future application of electronic equipment, perhaps the elimination of the insulation pinhole problem would have offered a compromise for consideration.

The installed cable plant, whether distribution, feeder or interexchange, represents a large investment, is at a fixed location and is the basic backbone for expansion by electronic or other means; therefore, one should insist that the cable plant be designed initially to optimize reliability and overall economy throughout the expected life of the plant. Full consideration must be given to what future performance is expected of the cable plant--not just today's performance.

Since telephone operating companies are users of materials, rather than designers, it should be obvious that the manufacturers have a unique challenge and opportunity. The immediate need is focused on two areas: (1) prevent future water entry into PIC cables (2) economically and safely restore existing wet cable to acceptable performance.

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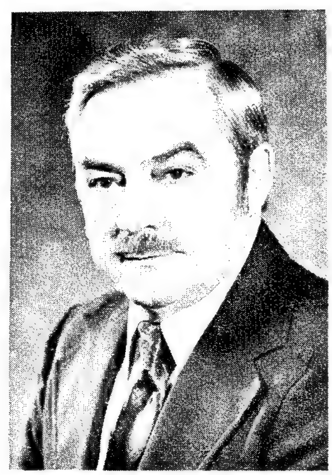

THE EFFECTS OF WATER IN PLASTIC INSULATED TELEPHONE CABLE

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Abstract

The effects of water in plastic insulated cable at various temperatures have been measured and are reported herein. Pulse reflectometry as a means of locating water is considered. The effects of reflections and increased attenuation resulting from water and ice in a cable on T-1 pulse code modulated (PCM) carrier system, as determined experimentally in the laboratory, are discussed.

Introduction

Since thermoplastic insulated telephone cables were introduced over 20 years ago many of them have operated despite various amounts of water in the core although occasional transmission troubles have been reported. In most cases the circuits would remain operative until the water bridged or grounded faults in the conductor insulation, consequently there have probably been small amounts of water in more cables than anyone has realized.

The effects of water in these cables, relative to the primary and secondary transmission constants, have been measured and reported previously.[1] At the risk of some oversimplification it can be said that the principal impairment to analog transmission in both non-loaded voice frequency circuits and in carrier systems was the marked increase in insertion loss due to the wet sections. This, however, was limited to the portions of the cable which were wet or filled with water and in many cases the overall effect on the circuit was relatively small and possibly not detectable without specific measuring scrutiny. Water in loaded cable will have substantially the same detrimental effect as increased load coil spacing. Where insulation faults existed, the presence of water could provide a conducting path to the cable shield or to another conductor with an insulation fault and the circuit or circuits could become very noisy or completely inoperative. Hence, through the years, there has been considerable emphasis on reducing the fault rate in conductor insulation during manufacture.

The advent of PCM carrier gave rise to some unexpected problems. An amount of water in a cable which did not cause any noticeable impairment of transmission at voice frequency or possibly even at an analog carrier frequency could cause an error rate which would be unsatisfactory or render the PCM system inoperative. When one is not aware that there is water in the cable this can be quite perplexing. It points up the necessity for checking in service cable thoroughly before placing PCM on it since satisfactory service for some other type of transmission is not in itself a valid check for a PCM system. In the interest of evaluation of in plant cables for PCM application, consideration has been given herein to methods of determining the presence and location of water in cable. The effects of water have also been evaluated as related to the PCM transmission of the T-1 carrier system (1.544 megabit per second data rate).

Methods of Determining the Presence and Location of Water in Cable

Pulse (time-domain) reflectometry is a convenient means to determine both the presence and location of water in cable. The presence of water causes the effective relative dielectric constant ($\mathcal{E}_r$) or specific inductive capacity (SIC) of the dielectric between conductors to be markedly different from that of normal cable and in turn causes a marked change in impedance, giving rise to pulse reflections which can be observed on an oscilloscope. Since the approximate velocity of propagation of the pairs is known or can be readily determined by simple experiment, the location of water-filled cable sections can be computed from the time scale of the oscilloscope display of reflected pulses. The velocity of propagation will vary somewhat from one cable to another, but for narrow pulses in a dry, 22 AWG 83 nF per mile cable an approximate figure is 720 feet per microsecond. This, of course, means that the distance from the source to the point of reflection is 360 feet per microsecond allowing for the go and return propagation. Water in a cable will slow the propagation of a signal depending on the degree of flooding. Cable that is fully filled with water will have a velocity approximately 66% that of dry cable. This complicates the time base, particularly if there are several flooded sections. The accuracy of location is, of course, not only a direct function of the time scale accuracy but also of how well defined the reflected pulses are. Narrow pulses are most suitable from this point of view because of their greater resolution of short and multiple discontinuities. On the other hand, narrow pulses are more rapidly attenuated because of their high frequency content. For this reason an echometer

with several pulse widths and high amplitude is desirable. The wider ones are suitable to detect water at long range and their exact locations may be more accurately determined by measurement from the other end of the repeater section using narrower pulses. The range of a reflectometer is also a function of pulse voltage and the gain of the detecting amplifier. The degree of flooding is also important in this regard. Even if a cable is water-filled in one section, a gradual variation in flooding from dry to completely filled can thwart the location because of the gradual rather than abrupt change in impedance which will be present. Because of this, there is no assurance that pulse reflectometry will always be successful in locating water, but two instruments which have been found useful for this purpose are W & G Instruments Inc. T 03/4 and the James G. Biddle Co. CME-110A.

Effects of Water on Cable Transmission at Temperatures above and below Freezing

The chief effect of water in cable is on the effective SIC of the dielectric of the pair. The SIC of pure water from 32 F (0 C) to 212 F (100 C) is accurately expressed by[2]

$$\varepsilon = 78.54\left[1-00460(t-25)+0.0000088(t-25)^2\right] \qquad (1)$$

where t is temperature of water in centigrade.

This is valid from dc up to about 100 MHz. The SIC calculated from equation 1 for a temperature of 55 F (13 C) is 83. In a water-filled PIC cable this causes the capacitance between the wire insulations of a pair to increase so sharply as to effectively short-circuit the external surfaces of the insulations. Under this condition the pair capacitance then attains a value very nearly one-half the capacitance from wire surface to dielectric surface (the "self-capacitance"), as it would be with individually shielded insulated wires. For No. 22 AWG PIC cable, with wire diameter of 25.3 mils and dielectric diameter of 44.0 mils, the pair capacitance will increase from 83 nF/mile (dry) to 186 nF/mile (wet) as calculated from:

$$C \cong \frac{1}{2}\,\frac{38.8\ \varepsilon}{\mathrm{Log}_{10} D/d}\ \mathrm{nF\ mile} \qquad (2)$$

where

ε = polyethylene SIC $\cong$ 2.3
D = diameter over dielectric (DOD)
d = conductor diameter

It is reported in the literature[3] that in the voice frequency range the SIC of ice is not substantially different from water at or near the freezing point; however, at frequencies up to 60 kHz it is both frequency and temperature sensitive. At higher frequencies it becomes more stable with both frequency and temperature attaining a value of about 3.1. This has not been borne out entirely by measurements in cable as evidenced by change in capacitance at temperatures below freezing, shown in Tables 2 and 3; however, greater temperature stability at higher frequencies is indicated.

There is good agreement at 772 kHz and 400 kHz at a temperature of 0 F as shown by capacitance values in Tables 1 and 3. As water changes from liquid to solid (ice), the capacitance of water-filled cable drops, but not to the level of dry cable. Soluble impurities do not have a significant effect on the SIC of ice at 60 kHz and above.

The presence of water increases the effective loss tangent and therefore the shunt conductance of a pair which is given by the familiar expression,

$$G = \omega C \tan \delta \qquad (3)$$

This also indicates that increased capacitance worsens the situation. Pure water has a loss tangent of 0.04 at 1 MHz and 25 C[4] as compared with established values of 0.0002 to 0.0005 for colored polyethylene.[5] Soluble impurities will affect the value for water. This effect is dependent upon temperature and the nature and degree of contamination and will, of course, vary with local conditions. Freezing has an influence on tan δ. Values cited for ice in reference 4 are 0.12 at 1 MHz and 0.035 at 100 MHz, both at -12 C. Measured values of G at 772 kHz shown in Table 1 appear to be reasonably consistent with the above.

Laboratory measurements were made on sections of No. 22 AWG PIC cable yielding primary and secondary parameters shown in Table 1.

Also shown in Tables 2 and 3 are data partially published[6] on the primary parameters of wet, damp, and dry 19 AWG PIC cable in the analog carrier frequency range.

The conditions wet, damp, and dry are defined as:

<u>Wet</u> - Cable core completely filled with water.

<u>Damp</u> - Cable core was completely filled with tap water, then suspended in a vertical position until the water ceased to drip from the cable ends.

<u>Dry</u> - Cable as manufactured.

It is seen that the capacitance of wet pairs behaves approximately as predicted and the series inductance is virtually unchanged by water and temperature. The high frequency characteristic impedance therefore is affected essentially by the effective SIC, hence by mutual capacitance, in accordance with the inverse ratio of square roots. The decrease in conductance for wet cable between 55 F and 100 F is probably caused by calcium sulphate found in tap water in parts of New Jersey where the tests are performed. What is of most interest is the phenomenal increase in conductance as water freezes, resulting in an attenuation more than twice that of dry cable and still considerably higher than in water-filled cable above freezing. It is this increased attenuation which no doubt precipitated field reports that T-1

Table 1

Primary and Secondary Parameters of Typical No. 22 AWG PIC Cable at 772 kHz

Temperature °F	R ohm/mile	L mH/mile	C nf/mile	G μ mho/mile	α dB/mile	β rad/mile	Z_o ohms/deg
A. Wet Cable							
100	536	0.806	185	21000	41.2	59.3	$66.4\angle -3.2$
55	510	0.797	186	26800	41.4	59.2	$65.7\angle -2.9$
0	475	0.801	125	83000	54.0	48.6	$79.9\angle 0$
B. Dry Cable							
100	532	0.807	80.8	665	22.3	39.3	$100.4\angle -3.8$
55	505	0.799	80.8	619	22.3	39.1	$99.8\angle -3.7$
0	478	0.799	80.6	513	22.3	39.0	$99.9\angle -3.5$

Table 2

Primary and Secondary Parameters at 150 kHz

Temperature °F	R ohm/mile	L mH/mile	C nf/mile	G μ mho/mile	α dB/mile	$\lvert Z_o \rvert$ ohms
A. Wet Cable						
68	162	0.816	182	2300	11.1	67.7
38	157	0.811	187	2700	11.0	66.6
26	154	0.814	158	26900	17.7	72.0
0	149	0.809	135	21000	15.4	77.6
-40	141	0.800	124	9800	11.0	80.9
B. Damp Cable						
68	162	0.806	106	1700	8.6	88.2
38	156	0.801	105	1700	8.4	88.3
26	153	0.801	100	5100	9.4	90.6
0	149	0.796	96	4100	8.7	91.9
-40	141	0.791	93	2900	7.8	92.8
C. Dry Cable						
68	162	0.818	83	26	7.0	100.6
38	157	0.813	82	24	6.8	100.5
26	154	0.797	82	23	6.8	99.5
0	149	0.808	82	24	6.5	100.2

Table 3

Primary and Secondary Parameters at 400 kHz

Temperature °F	R ohm/mile	L mH/mile	C nf/mile	G μ mho/mile	α dB/mile	$\lvert Z_o \rvert$ ohms
A. Wet Cable						
68	251	0.755	187	11800	20.4	63.9
38	242	0.756	186	13700	20.3	63.9
26	240	0.758	136	58470	32.9	74.4
0	233	0.757	124	31000	23.5	78.3
-40	221	0.749	120	13000	16.6	79.2
B. Damp Cable						
68	252	0.751	105	4590	14.6	85.0
38	243	0.746	104	4540	14.1	85.2
26	240	0.750	95	12600	16.6	89.2
0	232	0.746	93	8170	14.4	89.7
-40	220	0.742	91	4470	12.3	90.5
C. Dry Cable						
68	253	0.765	83	143	11.4	96.5
38	244	0.760	82	136	11.0	96.4
26	241	0.755	82	135	11.0	96.1
0	233	0.760	82	127	10.6	96.6

systems which have been working at temperatures above freezing have malfunctioned when temperature dropped below freezing.

The reflection coefficient $|\rho_{in}|$ at the input of a water-filled cable section of length ℓ_w which is terminated in an infinite length of dry cable can be calculated by the familiar expressions

$$\rho_{in} = \frac{Z_{in}-Z_o}{Z_{in}+Z_o} \tag{4a}$$

$$Z_{in} = Z_w \frac{1+\rho_w e^{-2\gamma_w \ell_w}}{1-\rho_w e^{-2\gamma_w \ell_w}} \tag{4b}$$

$$\rho_w = \frac{Z_o - Z_w}{Z_o + Z_w} \tag{4c}$$

Where:

Z_{in} is the input impedance of a water-filled cable section that is terminated with an infinite length of dry cable.

Z_o is the characteristic impedance of the dry cable.

Z_w is the characteristic impedance of the water-filled section.

ρ_w is the reflection coefficient from water-filled to an infinite length of dry cable.

γ_w is the propagation constant of water-filled cable.

The magnitude $|\rho_w|$ vs. ℓ_w is plotted in Figure 1 for a typical 22 AWG PIC pair at temperatures 0 F and 55 F. The curve for 100 F virtually coincides with that of 55 F since α and β, as indicated in Table 1, are almost identical. The curves reach first peaks of 0.35 and 0.21 at 55 F and 0 F, respectively, both of them occurring within a length range of 130 to 150 feet of wet cable. Following these first peaks are successions of damped minima and maxima converging on values 0.204 and 0.125, for 55 F and 0 F, respectively, as determined by (4c). The worst conditions of line reflection, therefore, are with wet lines of 130 to 150 feet rather than much longer lines. It is well to point out, however, that long flooded lines are more susceptible to error rate because of increased attenuation.

Effects of Line Reflections on T-1 Bipolar Repeater Performance

The effects of line reflections due to wet cable sections were measured with first generation line repeaters utilizing blocking oscillators in the output stage, or the regenerator, whose essential features are shown in Figure 2. A timing function is provided by clock signals which are derived from the time average of the incoming signals. This clock signal turns an output pulse on and off whenever a transmitted pulse is present at turn on time. An interfering pulse that is not coincidental with turn on time is not recognized and will not cause an error.

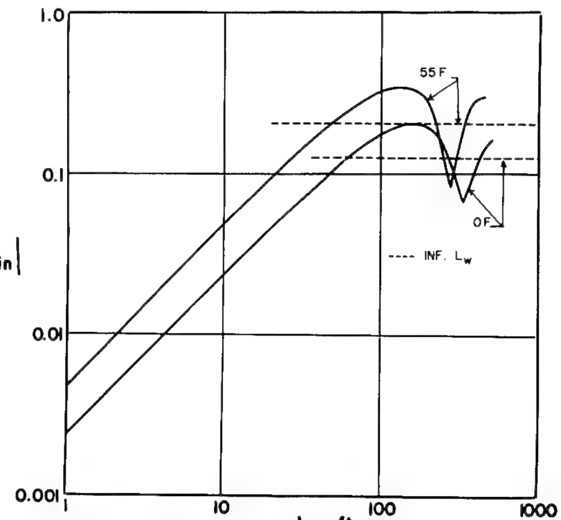


FIGURE 1: INPUT REFLECTION COEFFICIENT IN WATER FILLED NO. 22 AWG PIC PAIR AT 772 KHZ.

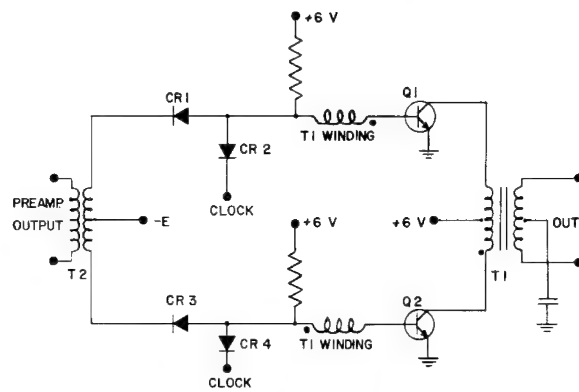


FIGURE 2: BASIC T-1 BIPOLAR REGENERATOR CIRCUIT.

It is noted, however, that feedback windings of the regenerator output transformer T-1 are connected to bases of transistors Q1 and Q2; hence any reflected voltage appearing at the output transformer appears also at the bases of Q1 and Q2. Depending on the magnitude, polarity and the timing of the reflected signal, it can increase or decrease the required preamplifier signal level necessary to initiate conduction. It follows that the regeneration of many pulses may be delayed or prevented or conversely that undesired pulses may occur. In less severe cases jitter may occur. Reflected pulses fed back into the regenerator can render the system more susceptible to impulse noise, crosstalk or distortion affecting the signal into the preamplifier.[7,8] Under certain conditions several effects can add and cause errors where the reflection by itself may not.

In the water-filled line tested, the maximum reflection coefficient at 772 kHz is approximately

1/3. The amplitude of a repeater output pulse is normally about 3 V. Since approximately +0.5 V at the bases blocking oscillator transistors is required to initiate conduction, pulses less than this value would not be expected to cause many pulse errors. The attenuation of dry cable is about 22 dB per mile or 4.2 dB per 1000 feet. Therefore, to reduce reflected pulses to less than 0.5 V, a round trip attenuation of 6 dB (3 dB each direction) requires a line length in excess of 700 feet. This distance will be modified by mismatches of the regenerator output to the nominally 100 ohm transmission line impedance and deviations of required transistor base-emitter conduction voltage. At a temperature of 0 F (water in a frozen state) a similar calculation would indicate a distance of about 200 feet.

In order to simulate field conditions, a few tests were made with the experimental set-up shown in Figure 3. A pseudo-random T-1 pulse generator was used to excite one pair of a one mile reel of No. 22 AWG PIC. This pair was terminated in the line repeater under test followed by about 6000 feet of cable in turn followed by a second line repeater terminated in a matching impedance. Both repeaters had sufficient line build-out attenuation inserted to provide a 32 dB total loss from cable and pads at 55 F. The cable following the unit under test was placed in a temperature chamber. A switching arrangement permitted the insertion of water-filled sections in this cable up to a total length of 310 feet in 10 foot steps. Also, sections of dry line, up to 1500 feet in 250 foot steps could be transferred from one side of the wet cable to the other side permitting the insertion of wet line from 0 to 1500 feet away from the repeater while maintaining constant length of line.

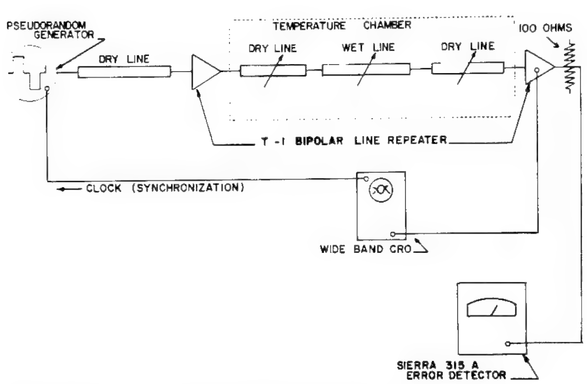


FIGURE 3: TEST SETUP - EFFECT OF WATER IN CABLE ON REPEATER PERFORMANCE.

A Sierra 315A error detector was connected at the output of the receiving repeater. The error detector flashes a light for any bipolar violation. Since virtually all pulse errors in this type of system result in such violation, the Sierra unit could detect essentially all pulse errors. The preamplifier output of this repeater was monitored by a wide band oscilloscope to observe the eye pattern of the pseudo-random pulse train. The eye pattern is a visual indication of jitter, faulty pulse timing and low pulse level at the input of this repeater. These factors increase vulnerability to error.

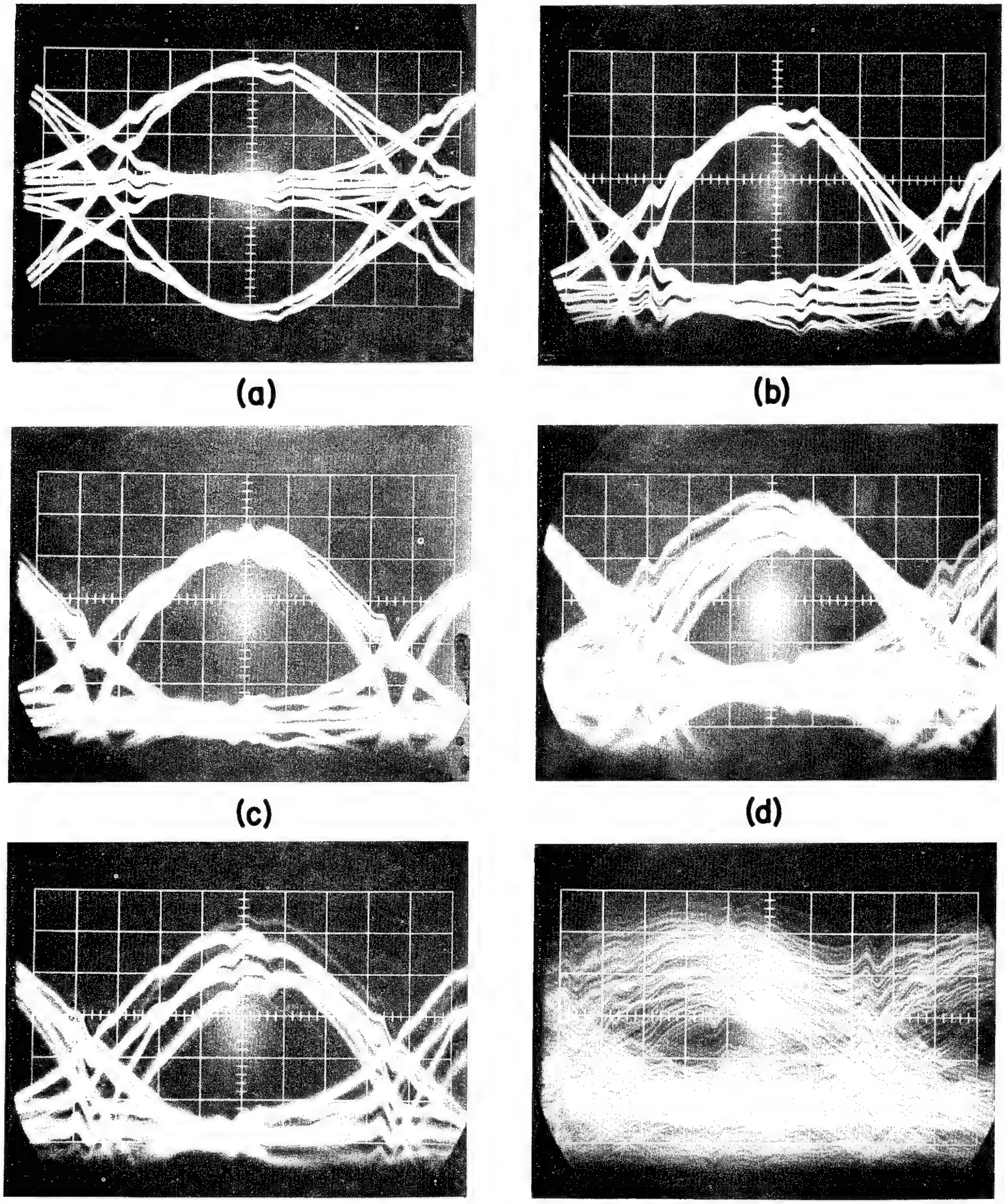
Measurements were made at 100 F, 55 F, and 0 F. Prior to measurements at each temperature, the cable was allowed to stabilize in the temperature chamber for at least 48 hours. Before activating the PCM units, the input reflection coefficient between a standard termination equivalent to a dry cable and the wet cable was measured with a Siemens hybrid bridge at 772 kHz. The calculated curves of Figure 1 were closely substantiated. The PCM units were then energized and the errors and eye patterns were recorded.

Error data was recorded as "occasional" (lamp flashes once for each error) and "frequent" (lamp stays on with possible slight flicker indicating more than 30 errors per second). In addition, the state of the eye pattern was noted. Data can be summarized as follows: At 55 F severe eye pattern distortions but no errors were observed with 30 feet of water separated from the repeater by up to 750 feet of dry line. Errors first appeared at 40 feet of water with up to 500 feet of separation. At 1000 feet separation frequent errors appeared with wet sections from 80 to 150 feet and from 240 to 310 feet in length, which is the longest wet section used. With separations over 1000 feet, few errors appeared. In most cases errors were accompanied by severe eye pattern distortions, particularly in the form of jitter, but also in the form of narrowed eye width and reduced height. Occasionally, however, severe distortions appeared without errors and errors appeared with only slight distortion.

The data at 100 F was in all respects very much the same as at 55 F. This was expected since the α and β of both dry and wet lines at these temperatures are not significantly different.

At 0 F, as might be expected from Figure 1, reflections caused far fewer errors. Although intermittent errors were observed with as much as 1,000 feet of dry cable separation for 140 feet of iced cable (the peak of the reflection coefficient curve), errors beyond 250 feet separation were rare. Some jitter and eye height reduction were observed up to 1500 feet for iced lengths greater than 30 feet, much as in the other cases. The first case of error did not appear before 80 feet of iced line was present.

Some typical eye patterns observed are shown in Figure 4. Oscillogram (a) indicates normal transmission (no reflections) at 55 F. Approximate symmetry exists about both time and voltage axes. Oscillogram (b) shows in more detail the upper half of (a). Oscillogram (c) is for the condition of 30 feet of water and 750 feet of separation at 55 F. There were no errors in this case but considerable jitter can be seen. Case (d) is for 80 feet wet and 500 feet separation at 100 F. Here again there were no errors but severe jitter, delayed regeneration, and reduced eye height can be observed. Although regeneration is



(a) (b) (c) (d) (e) (f)

FIGURE 4: EYE PATTERNS UNDER NORMAL AND FLOODED CABLE CONDITIONS.
Scales : (a)- none; (b)-(f) 0.5 V/cm , 100 ns /cm

often delayed, pulse turn-off is "on time." This is due to the sharply negative turn-off clock pulse which is unaffected by reflections. Reduced eye height always accompanies narrow pulses since a greater proportion of pulse energy is at higher frequencies where it is subject to greater attenuation. Oscillogram (e) is much like (d) but with less jitter. However in this case, occurring for 40 feet wet and 250 feet separations at 55 F, there were frequent errors. Case (f) for 80 feet wet and no separation, shows virtually complete destruction of the eye pattern and was accompanied by frequent errors.

Tests with the first generation T-1 repeaters used in the measurements have shown that reflections can cause errors with a rate that will render a line inoperable unless the source of reflections is sufficiently distant from the repeater. Repeaters have been developed and are currently available which, along with other improvements, have revised circuitry which makes them immune to reflected signals appearing at their output. Similar tests to those described herein have been made with the newer repeaters and have substantiated this immunity. These systems, as with the first generation, are affected by attenuation and distortion of signals into the receiving repeater. The increased losses due to water in the cable includes both increased attenuation of the wet section and the reflection losses at the interfaces of the wet and dry sections. As can be seen from Figure 1 and Table 1, the loss due to reflection can, depending on the length of the water-filled section, contribute more to the total loss than the added attenuation due to water. Losses that reduce the signal below a critical level will cause frequent errors or complete circuit failure. Distortion of the signal caused by water will increase the susceptibility of the system to crosstalk or other interference, or cause jitter which is cumulative in a repeater chain and may lead to crosstalk and distortion in the demodulated voice channel.[9]

Possible Consequences of Cable Reclamation Methods

There has been considerable interest over the years in reclaiming wet cable by removal of water. The success of such reclamation, even where it is feasible, is dependent on taking whatever measures are necessary to prevent the reentry of water into the cable.

Somewhat more promising methods have been developed where reclamation is accomplished by removing the water and filling the cable with a compatible material that will gel inside the cable so it will stay in place and protect against water reentry.

An experimental quantity of a material developed for Bell System, designated as "B Reclamation Compound," was obtained and pumped into a short length of water-filled cable in the laboratory. On the basis of calculated air volume of the original cable, the composition inside the cable after displacing the water was determined to be 81% B Reclamation Compound, 11% water and 8% air. This material in the cable increased the mutual capacitance approximately 30 percent over that of dry cable. It is understood that this can vary somewhat depending on the amount of water and air remaining in the cable. The effect on transmission properties is an increase in attenuation, a reduction in the velocity of propagation, and a reduction in impedance which will, of course, cause reflections at the interface of unfilled and compound filled sections of the cable. These effects will be dependent on what increase in capacitance actually results in any given installation. In any event the effects of the compound will be much less than water. While it appears that this material will be most useful for non-loaded voice frequency circuits, it cannot arbitrarily be ruled out for reclamation of loaded or carrier frequency circuits, but an evaluation should be made based on the length of the section to be reclaimed.

Conclusions

Reflections due to water or ice in cable can cause frequent errors in first generation T-1 repeaters unless the water-filled sections are very short or sufficiently removed from the repeater. Even where line reflections and attenuation do not by themselves render the line inoperable, the closed eye pattern indicates increased vulnerability to errors due to crosstalk and impulse noise. Also, jitter, as evidenced by the eye pattern, is cumulative in a series of repeaters and can build up to a severity that can result in distortion or crosstalk. Regardless of location, however, if sufficient length of cable is water-filled the system may fail because of increased attenuation.

This study indicates the need for stability in the transmission medium for PCM carrier systems and the prevention of any occurrences, particularly the entry of water, which will affect electrical uniformity. Where installation considerations permit, pressurization is often used as a means of monitoring sheath integrity and, in the event of damage, protecting against the ingress of moisture until repairs can be made. Also in the interest of transmission stability, thermoplastic insulated cables filled with a waterproofing compound have been developed and are gaining acceptance for use in outside plant.

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Mr. V. W. Pehrson received a BS degree in Electrical Engineering at Iowa State University in 1949. He was employed after graduation by General Cable Corporation. After assignments in the Research Laboratory and the Manufacturing Department, was transferred to the Application Engineering Department in 1954. He is presently Chief Engineer, Communications.

Mr. H. Simon received a Bachelor of Electrical Engineering degree from City College of New York in 1951 and an MEE degree from the Polytechnic Institute of Brooklyn in 1957. Prior to joining General Cable in 1964 he was employed at the Western Union Radio Engineering Laboratory and at the RCA Surface Communications Laboratory. He is presently a Senior Research Engineer in the General Cable Research Center.

RECLAMATION OF WATER-LOGGED BURIED PIC TELEPHONE CABLE

by

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Abstract

When water gets into buried polyethylene insulated conductor (PIC) telephone cable, it causes problems, some of them immediately service-affecting. The nature of the water problem in PIC cable and methods of restoration are discussed.

A new method of reclaiming water-logged buried PIC cable has been developed. The method entails pumping a low viscosity hydrophobic gelling compound into the cable. The compound, B Reclamation Compound, purges water from the cable. It is left in the cable to gel and block the re-entry of water. The design considerations in development of the compound and the effectiveness of the method are discussed.

Introduction

Multipair air-core polyethylene insulated conductor (PIC) telephone cable is designed with a .083 μf/mile capacitance and an insulation resistance in the teraohm range. Water in cables changes these parameters. It increases capacitance up to 140% above the design value and provides electrical leakage paths to conductors with insulation defects. Some of the consequences of water in cable are summarized in Table I.

Generally, the telephone subscriber will not notice the increased attenuation due to water in PIC cable. However, low insulation resistance and the accompanying problems of noise and conductor corrosion are service-affecting and are often the cause of subscriber complaints.

This paper describes the development of B Reclamation Compound* which is designed to restore the insulation resistance of water-logged PIC cables. Restoration is accomplished by purging water from the cable and filling it with a hydrophobic jelly.

TABLE I

CONSEQUENCES OF WATER IN PIC CABLE

WATER → UP TO 140% INCREASE IN MUTUAL CAPACITANCE

WATER → UP TO 55% INCREASE IN ATTENUATION

PINHOLES + WATER → LOW INSULATION RESISTANCES + UNBALANCED PAIRS

UNBALANCED PAIRS + POWERLINES → NOISE

LOW INSULATION RESISTANCE + BATTERY VOLTAGE → NOISE + CORROSION OF CONDUCTORS

VERY LOW INSULATION RESISTANCE ($<10{,}000\Omega$) → NO dc SIGNALING

Methods of Reclamation

An effective method for reclaiming water-logged cable must:

1) remove water present in cable,

2) restore the insulation resistance, capacitance and dielectric losses to acceptable values without corroding the conductors or stress-cracking the sheath or conductor insulation, and

3) prevent the re-entry of water into the cable.

Three approaches for reclaiming a water-logged cable that meet some or all of

---

* Appropriate patent protection is being sought.

the above criteria are to:

1) purge the cable,

2) purge the cable and seal insulation defects, and

3) purge and fill the cable.

The acetone method is an example of purge approach. Acetone, which is completely miscible with water and volatile, is pumped into the cable to purge water out. After all of the water is removed, the cable is purged with nitrogen. Some of the acetone is blown out and the remainder is allowed to evaporate.

The purge and seal approach is a variation on the acetone method. The objective is to have a sealant coat the insulation defects so that insulation resistance will remain high if water re-enters the core. The cable is purged with a compound containing a volatile solvent, which may be water miscible such as acetone, and a sealant. As in the acetone method, the cable is purged until all of the water is removed and then nitrogen is blown through the cable to remove some of the compound. The solvent is allowed to evaporate, leaving the sealant to coat the conductors.

The purge and fill approach employs a gelling compound to purge water from the cable. After water is removed, the compound is permitted to remain in the cable to gel, thus blocking the re-entry of water. The compound is hydrophobic and has high insulation resistance.

Materials Selection

One prime characteristic of a filling compound for the purge and fill method is viscosity. Low viscosity is necessary so that the material can be pumped into a section of telephone cable of sufficient length in a short time. A second characteristic is that its viscosity must increase once in place so that it cannot flow out through lightning pinholes or other sheath defects.

There are several classes of materials which satisfy the above requirements: thixotropic, gelling, and crosslinking compounds.

The development of a crosslinking compound which gels an oil was pursued since the viscosity of the system is dependent on the rate of a chemical reaction which can be controlled by use of a catalyst. Controlling the viscosities of gelling and thixotropic compounds is more difficult.

B Reclamation Compound is a urethane compound based on a hydroxyl-terminated liquid polybutadiene (polyol) and a castor oil-based isocyanate prepolymer disolved in a low viscosity aromatic oil. It cures to a jelly-like consistency in about 24 hours at 75°F.

The following design requirements were considered:

1) The cured compound must have good electrical properties.

   a) High volume resistivity. ($>10^{11}$ ohm-cm)

   b) Low dielectric constant, ($\varepsilon' < 3.0$)

   c) Low dissipation factor, ($D < .01$)

2) The viscosity should be < 50 centipoises at 75°F.

3) The liquid compound must cure in the cable in the presence of residual water.

4) The components must be hydrophobic.

5) The cured compound should wet the wire insulation.

6) The compound should be compatible with the wire insulation and the sheath, i.e., the integrity of the cable sheath and conductor separation must be maintained.

7) The cured compound should be reasonably permanent to justify reclamation costs.

8) The liquid components should have a reasonable shelf life (1 year).

9) The liquid compound should be safe to handle.

Dielectric Properties

The reclamation compound has reasonably good dielectric properties, Table II.

Table II

Dielectric Properties of Cured B Reclamation Compound

Frequency Hertz	ε'	D
10^3	2.6	0.005
10^4	2.6	0.001
10^5	2.6	0.002
10^6	2.6	0.004

Volume resistivity at 100 Vdc is $1.5 \times 10^{11} \Omega$ cm.

Viscosity Characteristics

The most difficult requirement was that of low viscosity. Numerous encapsulating compounds are available, but none have a room temperature viscosity near 50 centipoises. The reclamation compound has a viscosity of 20 centipoises at 75°F.

An empirical equation for the viscosity of two component blends (in this case, an oil and a polymer) is given by

$$\log \eta_s = (1 - A_p)\log \eta_{oil} + A_p \log \eta_p$$

where η_s is the viscosity of the solution, η_{oil} and η_p are the viscosity of the oil and the polymer, respectively, and A_p is the weight percent of the polymer in the solution. The equation is shown schematically in Figure 1. Three cases are shown: a) a low viscosity polymer in a low viscosity oil, b) a high viscosity polymer in a low viscosity oil, and c) a low viscosity polymer in a high viscosity oil. Figure 1 clearly indicates that the lowest viscosity compound would be a solution containing a minimum amount of low viscosity polymer in a low viscosity oil.

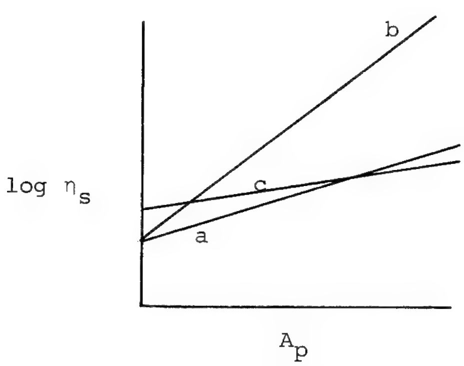
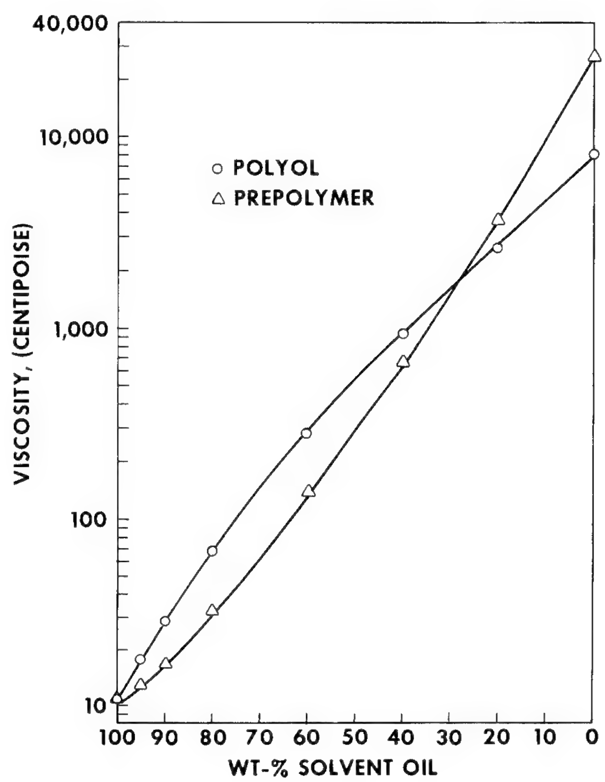


FIGURE 1. VISCOSITY SCHEMATIC OF VARIOUS BLENDS (SEE TEXT)

The objective was to minimize the viscosity of the compound and still have it gel. Since water interferes with the gelling reaction, it was necessary to allow a safety factor and use slight excess isocyanate.

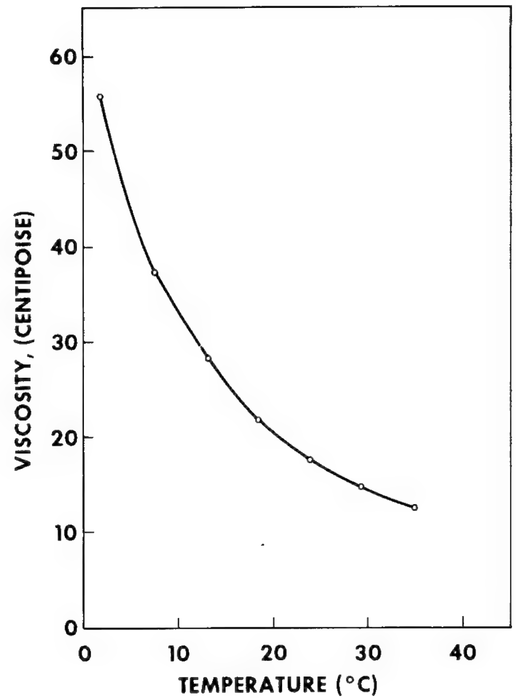
The viscosity/composition curves for the hydroxyl-terminated liquid polybutadiene and the isocyanate prepolymer are shown in Figure 2. Figure 3 is the viscosity/temperature curve for the compound. The catalyst was left out of this composition so it would not react appreciably while measurements were being taken. Note that at 10°C (50°F) the viscosity is double that at 24°C (75°F).

Figure 4 is a typical cure curve for the compound at 24°C (75°F). The gel time is approximately 24 hours. A series of viscosity/time curves were generated at various temperatures, and the gel times obtained from these curves are plotted in Figure 5.



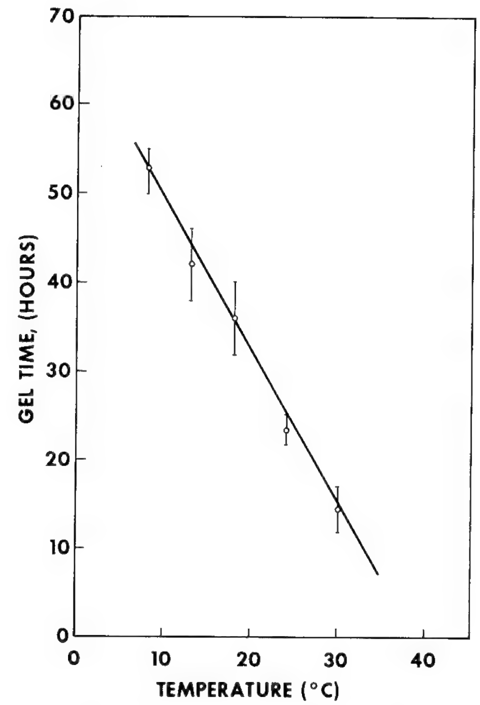
VISCOSITY OF COMPONENTS IN SOLVENT OIL

FIGURE 2



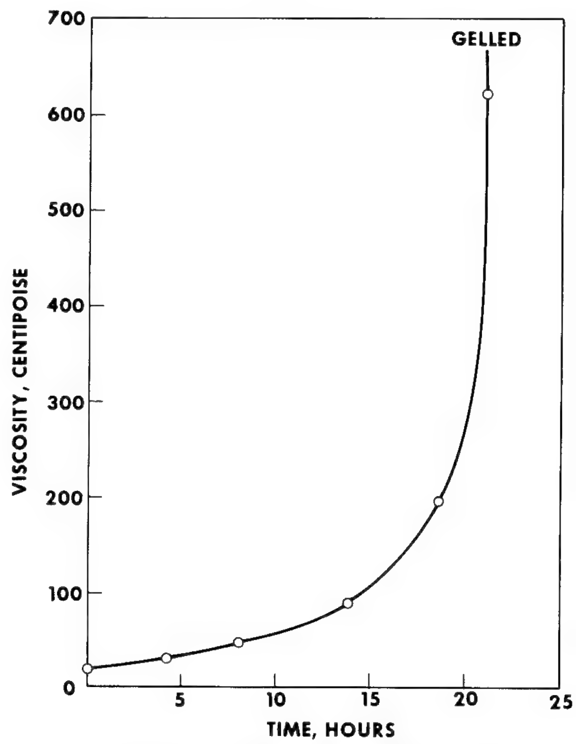
B RECLAMATION COMPOUND INITIAL VISCOSITY VS TEMPERATURE

FIGURE 3



B RECLAMATION COMPOUND GEL TIME VS TEMPERATURE

FIGURE 5



B RECLAMATION COMPOUND — CURE CURVE AT 24°C (75°)

FIGURE 4

Pumping Characteristics

The pumping characteristics of the compound were determined by pumping a 200 foot section of 50 pair 22 AWG PIC PAP cable. The shield and outer jacket of the cable were stripped off, leaving the translucent natural polyethylene inner jacket. The cable was first pumped full of water, and then pumped with the reclamation compound which was dyed red so that the advancing front could be distinguished. The compound, an early formulation, had a viscosity of 13 centipoises at ambient temperature, 75°F. Pumping was done with a positive displacement (piston) type pump at an average pressure of 90 psi. The results of this pumping experiment are shown in Figure 6 where the distance pumped is plotted versus the square root of the pumping time. The plot is nearly linear in agreement with Poiseuille's equation for laminar flow of an incompressible fluid through a pipe. Rearrangement of Poiseuille's equation yields:

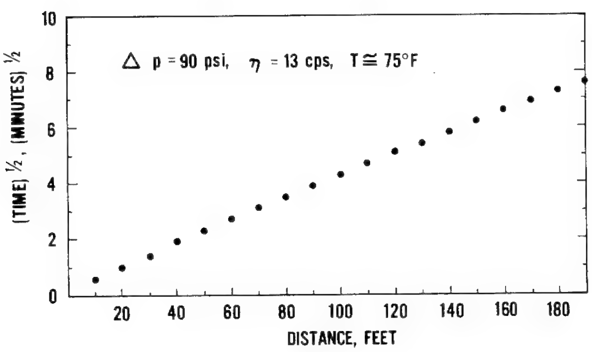
$$t_d = \frac{k\eta(T)}{\Delta p} d^2$$

where t_d is the time to pump distance d, $\eta(T)$ is the viscosity at temperature T, and Δp is the pumping pressure.

An exact fit to the above equation should not be expected since there are two

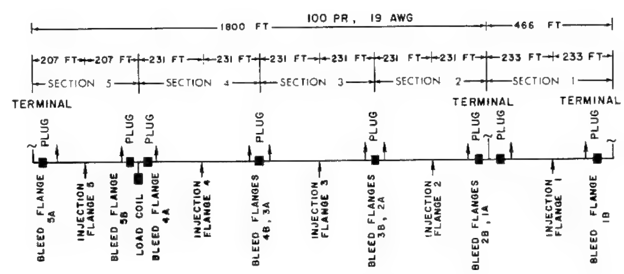
liquids in the tube, water and reclamation compound, and the components reacted during pumping.

chiefly on the labor sensitive procedures of cable preparation, leak locating and repair, and pumping. Compound cost is secondary.



PUMPING OF 200 ft 50 pr 22 AWG PIC PAP CABLE

FIGURE 6



CABLE LAYOUT – FIELD EXPERIMENT

FIGURE 7

Methods

The pump of choice is a modified 15 gallon paint spray tank. Pressure is supplied by a nitrogen cylinder. Modifications include a low level alarm and an automatic low level shut off valve to prevent pumping of nitrogen into the cable. Other pumps can and have been designed.

The cable is sectionalized and plugged into convenient pumping lengths. A typical layout is shown in Figure 7. Before the cable is reclaimed, it is pressure-tested to locate large leaks. The compound is injected into the cable core through a pressure flange. If the terrain permits, the flange is positioned near the center of the section which allows simultaneous pumping in two directions. Bleed flanges are placed at the ends of the sections to drain off water. Typical pumping times, in one direction, are shown in Table III.

Table III

Time to Pump 250 Feet of Cable, (Ground Temperature 75°F)

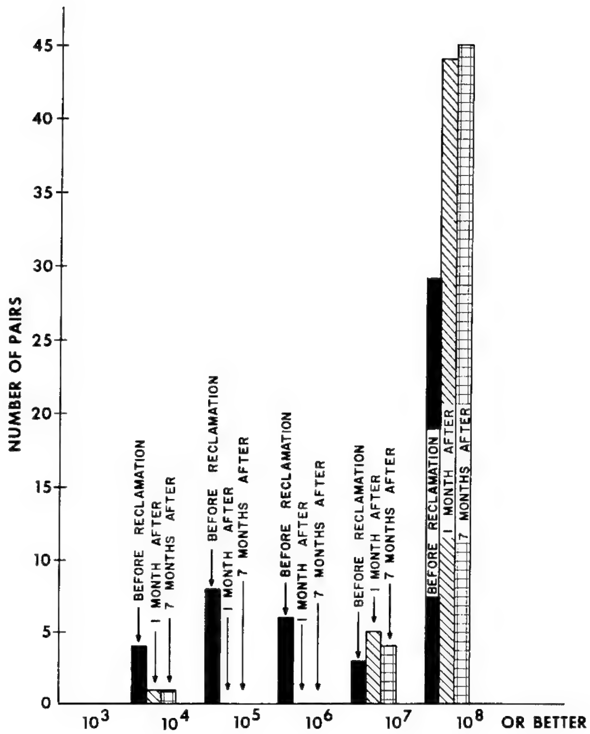
Cable Type	Pumping Pressure, psi	Time, Hours
100 pr 19 AWG	46	3
100 pr 22 AWG	55	4
100 pr 24 AWG	73	4
100 pr 26 AWG	83	9

The cost of cable reclamation depends

Electrical Results

Filling a dry cable with B Reclamation Compound results in an excess capacitance (over the dry value) of approximately 30%. Reclaimed cables have excess capacitances between 30% and 50% depending on the amount of water removed. Cables full of water have an excess capacitance up to 140%.

The main objective of the method is to restore and maintain the insulation resistance of defective pairs in the waterlogged cable. Results show that approximately 75% of those pairs in the waterlogged cable with low insulation resistance are restored to greater than 100 megohms by this method. Opens and shorts cannot be reclaimed by this procedure. The results of a typical reclamation are shown in Figure 8.



DISTRIBUTION OF INSULATION RESISTANCE VALUES

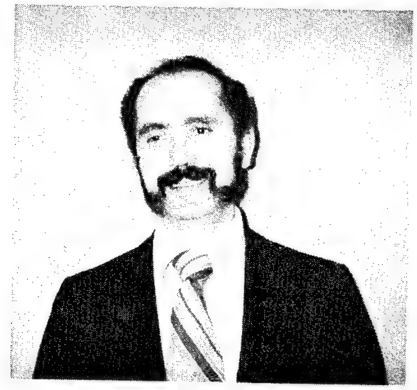
FIGURE 8

Acknowledgements

We gratefully acknowledge the contributions of our co-workers in the Bell System, particularly R. P. Guenther at AT&T, E. T. Lundgren at Western Electric, and R. Walker and D. R. Small at Bell Laboratories.

Stanley Kaufman

Stanley Kaufman is a Member of Technical Staff at Bell Telephone Laboratories. He received a B.S. in Physics from the City College of the City University of the City of New York, and a Ph.D. in Chemistry from Brown University. Before joining Bell Laboratories in 1970 he was a Research Scientist at the Uniroyal Research Center.



Raffaele Sabia

Raffaele Sabia, a graduate of St. Francis College of Brooklyn (B.S.) and Polytechnic Institute of Brooklyn, (Ph.D.), was employed by the Polymer Chemical Division of W. R. Grace prior to joining Bell Telephone Laboratories in 1963. Since 1963 he has been active in the research and development of materials for application in the wire and cable area and in the preparation of the text in the series "Physical Design of Electronic Systems" published by Prentice Hall. Since 1967 he has been supervisor of the Chemical Engineering Group in the Transmission Media Laboratory.

Treatment of Degraded PIC Insulation in Pedestal Closures Associated with Buried Plant

J. W. Shea

Bell Laboratories

Summary

For some time now, cracking of PIC insulation in pedestal closures associated with buried plant has been observed in some areas of the country. To overcome this problem without expensive rewiring of the closures, a field-applied spray insulation has been developed. The material has been evaluated in terms of electrical properties, thermal characteristics and application techniques.

Introduction

Over the past years, distribution cable for telephone use has been manufactured using low density polyethylene insulation on copper conductors. In some areas of the country, particularly the southwest, there have been instances where insulation failures have occurred in pedestal closures due to oxidative degradation. This degradation can be severe enough to cause the insulation to fall off the conductor. The result is a series of failures in closures causing repeated service calls to the affected area.

The insulation failures have been found only in pedestal closures where the sheath has been removed from the cable. An obvious solution is to cut out the failed wires and rewire the terminal. This is a very expensive procedure, requiring an estimated four to seven hours for two craftsmen. It was therefore decided to try to develop a method of covering the cracks and bare wires in the affected closures. To effect this it would be necessary to provide an inexpensive coating, easily applied, which would have good electrical characteristics, dry rapidly, be thermally stable at pedestal temperatures, have good clarity so color coding would not be affected, and have no effect on hardware normally used in the closures.

Preliminary Testing

Prior to testing of potentially useful materials for this application, a survey of pedestal hardware was carried out. This revealed that Scotch-Lok splicing connectors (manufactured by 3M Corporation) and 700 series splicing connectors (manufactured by Western Electric Company) are made from polycarbonate. This material, especially in the stressed condition of crimped connectors, is susceptible to stress cracking by a variety of solvents. Available stress crack data indicated that any system coming in contact with these connectors should contain only alcohols or aliphatic hydrocarbons as a solvent.

With this limitation in mind, a series of materials were screened for possible use. (In the testing, the wire arrangement in field pedestals was simulated through the use of pedestal mock-ups as shown in Figure 1). Four materials were selected for screening based on availability, compatibility with suitable solvents, and electrical characteristics of the material class. A spray material currently being sold for restoring degraded insulation was included in this series. Initially, color retention and flexibility were examined. Flexibility was evaluated by bending a sprayed wire at 180° and visually examining it for cracks. The results of preliminary screening are shown in Table I. The aliphatic polyurethane system gave the best results in these tests.

Electrical characterization was done by spraying mock-up pedestals with four of the above materials. Cracked insulation was simulated by removing insulation sections from one-sixteenth inch to one inch from wires in the mock-up. The commercial material was sprayed from the aerosol can in which it is sold. The three other materials were sprayed using a portable spray unit, the Jet-Pack* *(Sprayon Products, Inc.,Cleveland, Ohio). (Fig 2).

This unit consists of a can of compressed propellant, a container for the solution and a cap which provides a spray nozzle and a plunger for propellant release. The three materials were sprayed from isopropanol solution. Mock-up pedestals were prepared using two or three coats of material. With the acrylic and the commercial spray, the pedestals were apparently not completely covered in some areas. In these cases only the three coat samples were tested.

The samples were air-dried for twenty four hours and insulation resistance was measured on a Boonton Radio megohm bridge. Resistance was measured at 50V potential between a specific wire pair and a bare copper wire suspended in first tap water and then a 16% salt solution. Reference values were determined by measuring the resistance between two bare copper wires in the tap water and salt solution. The tap water gave a value of 10^3 ohms while the salt water reading was below the 900 ohm minimum bridge reading. The results for the sprayed wires are given in Table II.

The two urethane materials gave the best results in these tests. Pedestals sprayed with these materials were placed in an air circulating oven to 90°C. After two weeks the aromatic polyurethane had yellowed quite badly and it was not possible to distinguish yellow and white wires. The aliphatic polyurethane showed no change in color, remaining completely clear. As a result of these screening tests, the aliphatic polyurethane was selected for further evaluation. All subsequent testing was carried out using this material.

Humidity Resistance

Insulation resistance after humidity exposure was done using a standard printed circuit test. An interleafed copper pattern (Figure 3) was sprayed with the aliphatic polyurethane and exposed at 95°F and 91% R.H. A 45 D.C. potential was applied during the exposure. After eleven days the sample was tested for insulation resistance at 500V. All samples gave values $\geq 10^8$ ohms.

Spraying Procedure

Mock-up pedestals were sprayed using various procedures. Some were sprayed lightly with two coats, some lightly with three coats, and some received a heavy three coat spray. Random measurements gave a coating thickness of 1-3 mils with three light coats and 4-7 mils with three heavy coats. Because of the mock-up geometry, coating is not uniform. Visual observation indicates that the light spray left some wire areas with no coverage. Liberal spraying yields pedestals which, on visual inspection, have some coating on all wires. Insulation resistance results are given in Table III. The results confirm the need for three heavy coats to obtain complete defect coverage.

Thermal Stability

Mock-up pedestals were prepared for evaluation of thermal stability. In these cases insulation was removed from adjacent areas of a single pair. No attempt was made to separate these wires before spraying. As a result some pairs had bare wires in very close proximity and may have had wires touching. Insulation resistance was measured between wires of a given pair with the results shown in Table IV. In all cases where a value of less than 10^6 ohms was recorded, it was associated with two bare wires in very close proximity. These results emphasize that, where insulation has failed on two closely spaced wires, the wires must be separated before spraying to ensure adequate coverage.

All pedestal mock-ups were placed in an air circulating oven at 90°C. Insulation resistance was measured periodically. After 1000 hours no decrease in insulation resistance was observed. The coating remained clear with no change in insulation color.

Oxygen uptake testing was carried out on samples of PIC insulation, sprayed and unsprayed, and on copper wire sprayed with the aliphatic urethane. The PIC insulation failed in 20 hours at 120°C. The PIC insulation with a sprayed coating failed in 60 hours. The urethane material on copper was removed after 168 hours with no apparent signs of failure.

Effects on Splicing Connectors

During normal operations, PIC wires in pedestals are often spliced with small splicing connectors. To insure that spraying did not interfere with this operation, sprayed wires were spliced and checked for continuity. Scotch-Lok VG and Scotch-Lok VR connectors from 3M Corporation as well as 700-2A, 700-3A and "B" wire connectors from Western Electric Company were used in this test. In all cases no interference with splicing effectiveness was found. After continuity testing the samples were resprayed to check the effect of the spray on the connectors. No

evidence of any stress cracking of the connectors was noted.

Polyethylene Stress Cracking

Polyethylene can stress crack at or near its yield point. Since insulations can be stressed in closures by clamping, pigtailing, etc., stress crack tests were performed.

Sheathing was tested for cracking by spraying the sheath area of mock-up pedestals and examining for cracks after two weeks at room temperature and at 90°C. PIC wires, in the form of pigtails and 1/4" diameter coils, were sprayed and aged at 90°C and also immersed in isopropanol. In no case was any evidence of cracking found.

Packaging

Two methods of packaging were investigated. One was the use of an aerosol can. The second was the commercial portable spray unit previously discussed. Both methods gave good results. The aerosol can was selected as being more convenient for general field use.

Field Experiment

A field experiment involving approximately 100 pedestals was carried out in Tucson, Arizona. The insulation in these pedestals was, in general, badly deteriorated and service calls to the area had been running at a high rate. The wires in the pedestals were spread apart and a liberal coat of spray applied, paying particular attention to the obvious defects. The material was allowed to dry and a second liberal coat applied. After this had dried, the wires were placed in their original position and a third coat applied. In this manner, three pedestals per man-hour could be sprayed at temperatures as low as 70°F.

Two months after spraying,the test site was revisited to examine these pedestals. The coated conductors were in good condition. Attempts to peel the coating from degraded insulation resulted in elongation of the coating followed by tearing. The peeled coating had polyethylene insulation embedded in it, indicating good adhesion to the insulation. Copper conductors showed no oxidation or corrosion effects under the coating. No effect on any terminal hardware was found.

In the sixty-day period following application of the coating, three trouble reports had been received from the treated area. One was traced to a wire pinched between the pedestal cap and the pedestal bottom. A second was caused by a short to ground by an insufficiently sprayed wire. A report on the third call was not available. In areas of comparable size and insulation age in Tucson, 15 to 20 service calls are received on the average in a sixty-day period. The spray treatment of the area had resulted in a significant reduction in service calls.

One year after the test spraying, reports from the area show that, in low activity areas, the original spray insulation is performing well. In high activity areas, some tearing of spray insulation has resulted from repeated handling of the wires. To prevent problems from occurring as a result of this tearing, a practice calling for a single re-spray of the insulation after working in a high-activity terminal has been established.

Conclusions

A restorative spray for degraded PIC insulation in pedestal closures has been developed. The material has good electrical and thermal characteristics, can be readily applied in the field, and has no effect on terminal hardware. Application of the spray to closures in the field significantly reduces service calls resulting from degraded insulation.

Biography

Mr. Shea received a B.S. in Chemistry from King's College, Wilkes Barre, Pennsylvania in 1952 and a M.S. in Physics in 1954 from the University of Notre Dame. He joined the Bell Telephone Laboratories as a member of the Technical Staff in 1967, working on materials for printed circuits. Prior to that time, he spent ten years at Union Carbide Corporation working on thermosetting resins for industrial laminates. He is currently a member of the Materials Chemistry Group at the Bell Telephone Laboratories, Atlanta, Georgia, engaged in development of materials for cable.

FIGURE 1 - PEDESTAL MOCK-UP

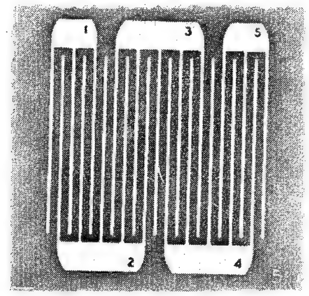


FIGURE 3 - INSULATION RESISTANCE SPECIMEN

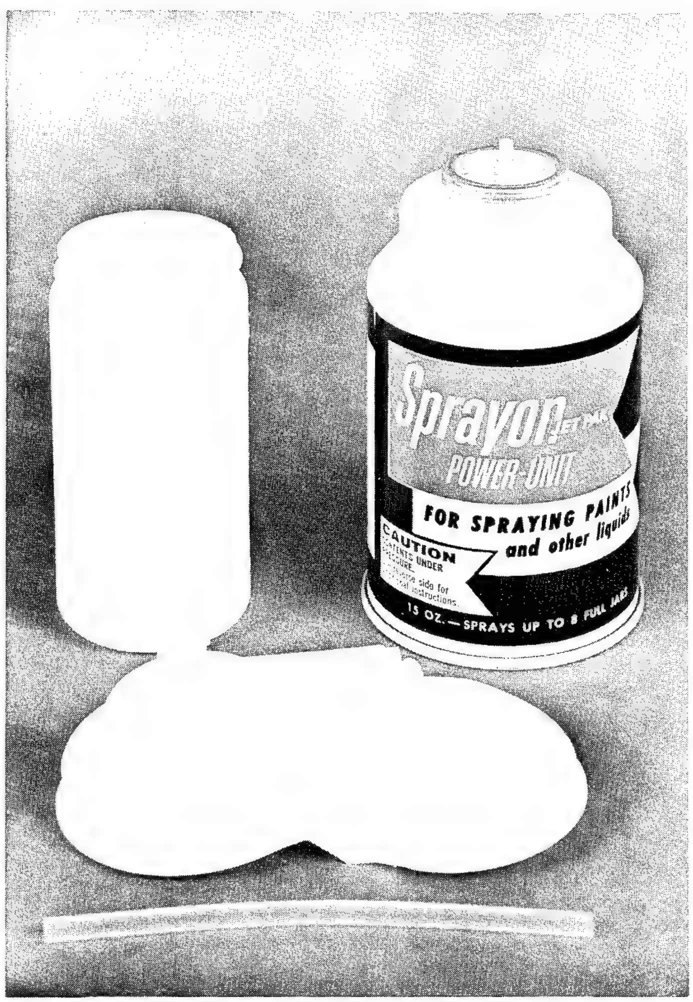


FIGURE 2 - JET PACK SPRAY UNIT

TABLE I - PRELIMINARY SCREENING TESTS

MATERIAL	COLOR RETENTION	FLEXIBILITY
Aromatic Polyurethane	Fair	Good
Nitrocellulose Lacquer	Good	Poor
Aliphatic Polyurethane	Good	Good
Acrylic	Good	Poor
Polyvinyl Acetate Type (Commercial System)	Fair	Poor

TABLE II - INSULATION RESISTANCE, OHMS

MATERIAL	TWO COATS		THREE COATS	
	TAP WATER	16% SALT WATER	TAP WATER	16% SALT WATER
Aromatic Polyurethane	10^5	10^3	10^{11}	10^9
Aliphatic Polyurethane	10^5	10^3	10^8	10^9
Acrylic			10^9	10^4
Commercial Material (Polyvinyl Acetate Type)			10^9	10^3

TABLE III - SPRAYING PROCEDURE RESULTS

ALIPHATIC POLYURETHANE RESINS

COATING	INSULATION RESISTANCE, OHMS	
	TAP WATER	16% SALT WATER
2 Coats, Light	7 Values @ 10^4 5 " @ 10^5 2 " @ 10^6 1 " @ 10^7	15 Values @ 10^3
3 Coats, Light	1 Value @ 10^4 2 " @ 10^5 5 " @ 10^6 1 " @ 10^7	9 Values @ 10^3 1 " @ 10^4 3 " @ 10^6 2 " @ 10^7
3 Coats, Heavy	1 Value @ 10^7 3 Values @ 10^8 10 " @ 10^9 1 " @ 10^{10}	6 Values @ 10^7 9 " @ 10^9

TABLE IV

INSULATION RESISTANCE, OHMS

THERMAL STABILITY SAMPLES

PEDESTAL NO.	RESISTANCE, OHMS
1	1 @ 10^7 4 @ 10^9
2	1 @ 10^3 1 @ 10^4 1 @ 10^5 1 @ 10^7 1 @ 10^8
3	1 @ 10^4 3 @ 10^8 1 @ 10^9
4	1 @ 10^6 4 @ 10^8
5	2 @ 10^8 3 @ 10^9

SULFIDE ATTACK TO POLYETHYLENE INSULATED CONTROL CABLE AND DEVELOPMENT OF SULFIDE CAPTURE SHEATH

Teruo Fukuda Toyokazu Hisatsune Hiroshi Nagai Morikuni Hasebe

All of: The Furukawa Electric Co., Ltd. Tokyo, Japan.

1. SUMMARY

A new type of deterioration involving sulfide attack was discovered in a polyethylene insulated control cable installed in a chemical plant. This paper presents the mechanism of the sulfide deterioration, sulfide trees, and the development of sulfide capture sheath as a preventive measure.

2. INTRODUCTION

Recently, the demand for cables insulated by solid dielectrics like plastics has been increasing enormously in Japan. Especially, polyethylene (including cross-linked polyethylene) is widely applied as an insulating material because of its excellent electrical, physical and chemical characteristics. However, a new deterioration in the polyethylene (PE) caused by moisture and/or chemicals permeation, has been found and it often leads to an eventual insulation failure. (1) - (6)

This deterioration is caused by environmental pollution that has now been spread over the locations where cables are installed. As the pattern of environmental pollution is very complicated, the cable deterioration is seen in an intricate and varying manner.

This paper presents the deterioration phenomenon of the PE insulated cable by sulfides and its preventive method. First, a control cable short-circuited by sulfide trees (6) is reported in detail; next, a sulfide capture cable is explained, which we have developed to prevent sulfide trees. This cable has an excellent function for a direct buried cable or a submarine cable in the environmental pollution area.

3. DETERIORATION DUE TO SULFIDE TREES

The deterioration due to sulfide trees is one of the patterns of chemical treeing. "Sulfide trees" is defined as follows:

Sulfides, such as hydrogen sulfide (H_2S), permeate through the jacket and insulation of a cable to finally reach the metallic conductor. Copper conductor reacts with sulfides to produce cuprous sulfide (Cu_2S) which crystallizes and grows into the insulation to form a dendritic deposit or trees. If the dendrites of cuprous sulfide, which are conductive materials, continue growing through the insulation, an ultimate voltage breakdown will occur.

In the following the morphology of sulfide trees and their growth mechanism are reported taking the case of a control cable that broke down in service due to sulfide trees.

3-1 Troubled Cable

A trouble occurred for the first time to a control cable with PE insulation and polyvinylchloride (PVC) jacket (600V 3 x 3.5 mm^2): an insulation breakdown in the sixth year of operation. The troubled cable had been submerged in water in an open duct as shown in Photo. 1.

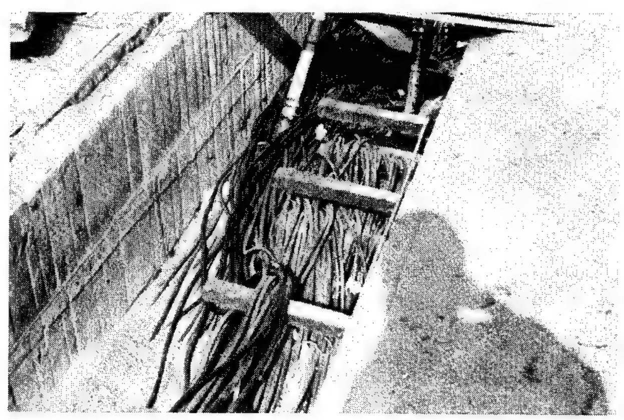


Photo. 1. Troubled Cable in an Open Duct.

The water was found to contain chlorine ion ($C\ell^-$), ammonium ion (NH_3) and 0.02 mg/ℓ sulfur ion (S^{--}). The cable had been used for six years, but it was not known how long it had actually been submerged or what sulfide concentration the water had during that period.

No change in the appearance of the cable was observed (Photo. 2). The cable was dissected to determine, if possible, the cause of the failure. Many black

spots were found on the surface of PE insulated core. The copper conductor was heavily corroded and black dendritic deposition extending into the PE was **observed**.

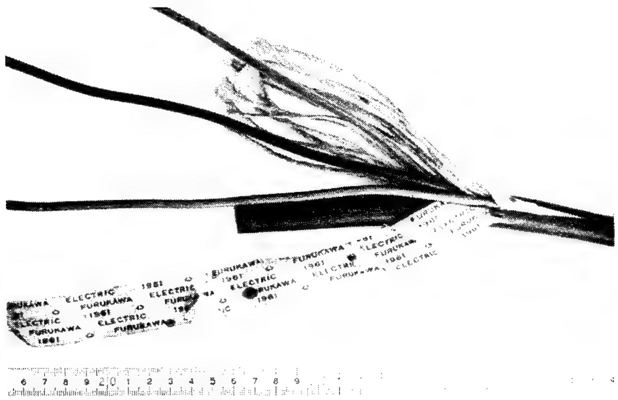


Photo. 2. Troubled Cable due to Sulfide Trees.

3-2 Distribution and Shape of Sulfide Trees

The ten specimens were randomly cut from the cable to determine the distribution of sulfide trees. As shown in Fig. 1, it was found that most of sulfide trees

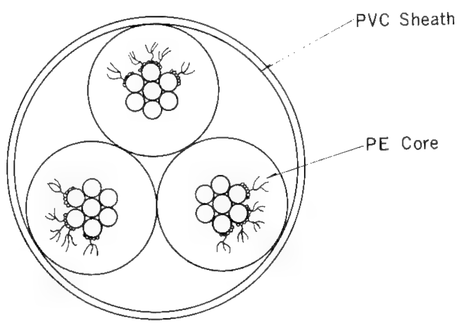


Fig. 1. Distribution of Sulfide Trees in a Cross-Section of Cable Stranded Three Core.

grew and developed at the area of the insulation which was positioned close to the PVC jacket.

Fig. 1. illustrates the distribution of sulfide trees in

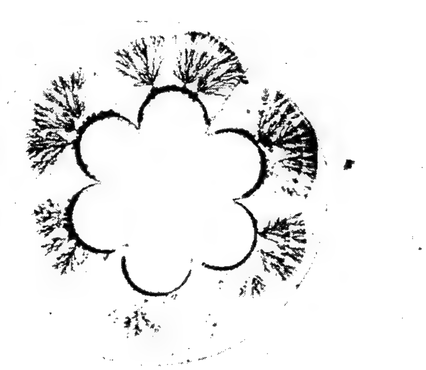


Photo. 3. Distribution of Sulfide Trees in a Core, PE Insulation is 1 mm Thick.

the cross section of a three-core cable. The cross section of a core is shown in Photo. 3, which illustrates the distribution of sulfide trees in a core. In this figure, most of the sulfide trees are located in direct contact with the jacket.

It is noted that sulfide trees originate usually from the convex part of the stranded conductor (or at the concave part of the insulation) and almost none at the concave part of the stranded conductor (or at the convex part of the insulation). One of the typical sulfide trees is shown in Photo. 4. As clearly seen from it, sulfide trees can be classified into two types from the viewpoint of growth habits:

(1) Bush-like growths (Photo. 4, Arrow A)

(2) Tree-like growths (Photo. 4, Arrow B)

Bush-like growths start from the PE areas in contact with the stranded copper conductor, while tree-like growths start from the tips of the bush-like patterns.

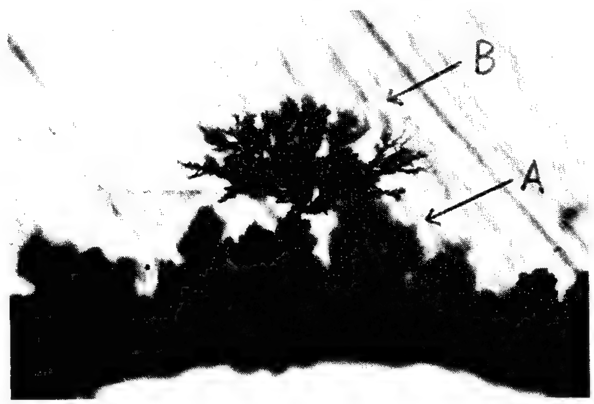


Photo. 4. Typical Sulfide Tree
The Length of Sulfide Tree is 100 micron.

It can be seen in Photo. 4 that one of growth forms is round like clusters of grapes at terminal points on the tree.

These differ in shape from the trees which could be produced by the voltage field concentration in PE insulated power cables. (7)

3-3 Identification of Sulfide Trees

As previously mentioned, there was little change in the appearance of PVC jacket. No significant deterioration of mechanical properties of PVC was noted. In order to study the chemical deterioration, the plasticizer, PVC resin and filler were refined and separated. No change was found in the plasticizer or the resin.

However, X-ray diffraction analysis of the filler showed the existence of substantial amounts of PbS (lead sulfide) as shown in Table 1. PbS was not contained in the original jacket. Generally, in PVC compounds, heat

Table 1. X-ray Diffraction Analysis of Filler.

FILLER d(Å)	PBS d(Å)*
1.143	1.14 (6)**
1.211	1.21 (10)
1.329	1.32 (17)
1.362	1.36 (10)
1.486	1.48 (10)
1.715	1.71 (16)
1.790	1.79 (35)
2.103	2.09 (57)
2.978	2.96 (100)
2.037	
3.439	3.42 (84)

* FROM ASTM CARDS.
** DIFFRACTION INTENSITY.

stabilizers such as $3PbO \cdot PbSO_4 \cdot H_2O$ (tribasic lead sulphate) are utilized. It may be concluded that these lead compounds reacted with sulfides to produce PbS. In addition, a large amount of sulfur was also detected in the surrounding cotton tape and jute.

X-ray diffraction analysis was made on the black corrosive products found on the copper conductor in contact with the insulation. The results are shown in Table 2 which illustrates the diffraction intensity of corrosive products. It is clear that these corrosive products are composed of crystalline Cu_2S and Cu_2O (couprous oxide).

Table 2. X-ray Diffraction Analysis of Black Corrosive Products.

CORROSIVE PRODUCTS	STANDARD (FROM ASTM CARDS)			
	Cu_2S	Cu_2O	CuO	CuS
d (Å)	d (Å)	d (Å)	d (Å)	d (Å)
3.04		3.02 (9)	2.75 (12)	3.22 (28)
2.46		2.46 (100)	2.52 (100)	2.81 (100)
2.41	2.40 (70)*		2.32 (96)	2.72 (56)
2.12		2.13 (37)	2.31 (30)	2.31 (10)
1.95	1.96 (80)		1.87 (25)	1.90 (25)
1.86	1.87 (100)		1.71 (8)	1.89 (75)
1.68	1.69 (40)		1.58 (14)	1.73 (34)
1.50		1.51 (27)	1.51 (20)	1.56 (37)
1.28		1.28 (17)	1.41 (15)	1.35 (7)

*DIFFRACTION INTENSITY.

From the results of X-ray diffraction measurements of several areas, the diffraction intensities of Cu_2S and Cu_2O differ from each other. Therefore, the ratio of Cu_2S/Cu_2O is not constant.

Results of X-ray microanalyzer tests carried out on the cross sectional areas are shown in Photos. 5-7. In the analysis, the characteristic X-rays were measured of Cu (Copper), S (Sulfur), O (Oxygen), Ni (Nickel), Cr (Chromium) and Fe (Iron). Ni, Cr or Fe was not observed. The characteristic X-rays of oxygen could not be confirmed because of its weak intensity.

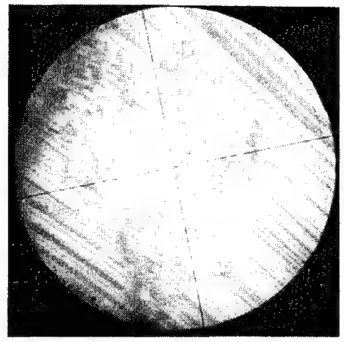


Photo. 5. Sample of X-ray Microanalyzer Opticalscopic Shape of Sulfide Tree.

X-ray Characteristics Pattern.

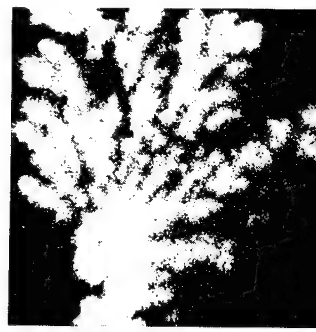


Photo. 6. Copper.

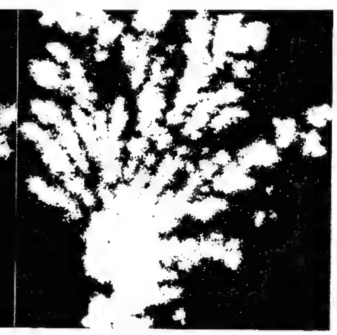


Photo. 7. Sulfur.

As is clear from these photographs, the characteristic patterns of the X-ray-microanalyzer agree very well in shape with the corresponding patterns of optical microphotographs. Evidently, sulfide trees are at least composed of Cu and S. Therefore, it may be concluded from the X-ray diffraction analysis and the X-ray microanalyzer that the sulfide trees are composed of Cu_2S and Cu_2O.

3-4 Growth Mechanism of Sulfide Trees

On the basis of these investigations and analytical results, the mechanism of sulfide tree formation will be discussed.

To begin with, there should be sufficient amounts of sulfides such as H_2S and ammonium sulfide in the cable environment. They proceed to permeate into the cable either in their own form or in its aqueous solutions.

The permeation of sulfides was confirmed by the formation of PbS in the PVC jacket (Table 1) and the detection of sulfur in cotton tape and jute. Sulfides permeate through the PE insulation and react with the copper conductor to produce cuprous sulfide (Cu_2S). An electron diffraction analysis showed that this cuprous sulfide was an orthorhombic type α -Cu_2S.

The crystalline Cu_2S penetrates into the insulation due to the pressure which is produced by the volumetric change by its crystallization. These deposits formed themselves into the bush-like growths. The bush-like growth is always observed in the troubled cables, irrespective of an applied voltage. Also it can easily be reproduced in the laboratory.

It seems that the bush-like pattern grows into the insulation wherever copper is in intimate contact with the insulation.

Following that, an electrical field would concentrate at some portion of the bush-like growths, after which the tree-like growth is developed at that position by an electrical action.

The tree-like growth does not develop into an insulation without an applied voltage. However, the tree-like growth does not always develop even if voltage is applied.

The expanding direction of sulfide trees appeared to be affected by the permeating direction of the sulfides (Fig. 1) and it was not evident what effect the electric field had on this direction.

The corrosive reaction continues on the copper conductor and the bush-like and tree-like growths proceed into the insulation as long as sulfides permeate from the outside.

The cuprous sulfide is oxidized with time to change into Cu_2O, and therefore, Cu_2S and Cu_2O co-exist in the growth patterns. As the degree of oxidation increases, Cu_2O becomes richer.

Cu_2S and Cu_2O, being conductive in nature, result in a short circuit whenever the sulfide trees completely penetrate through the insulation.

However, no remarkable reduction of insulation resistance is observed so long as the sulfide trees growing in the PE insulation have not penetrated through it yet, because of a very good resistivity of PE. Thus, the sulfide trees cannot be found from the outside; this makes it more difficult to detect the trees.

As is clear from these examples, sulfides can permeate through PVC and PE easily beyond our expectations. Further, it is confirmed that the insulation of non-filled polymer like PE is easily affected by the corrosion of metals. Therefore, for a control cable or a submarine cable without a metallic sheath, there is a great possibility of sulfide trees appearing if sulfides exist.

4. PREVENTION OF SULFIDE TREES

4-1 Key to Prevention

Since sulfide trees are caused by the coexistence of sulfides and copper, the principle of prevention is to eliminate either sulfides or copper. From our experiments, practicable methods of prevention and their effects are summarized in Fig. 2.

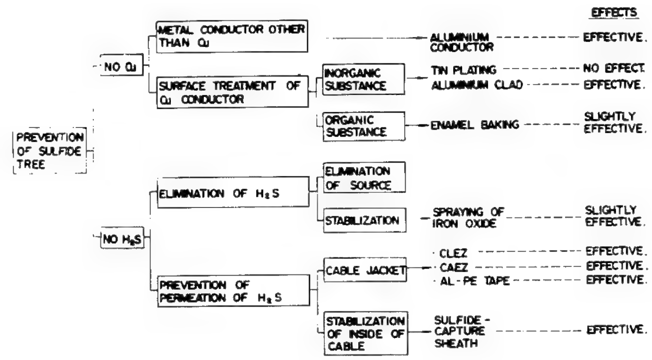


Fig. 2. Prevention of Sulfide Trees.

4-2 Effects of Prevention

The preventive method wherein the copper conductor is replaced by an aluminum conductor is completely effectual against sulfide trees. However, it is not possible to replace all copper conductors with aluminum, because aluminum is inferior to copper in conductivity and alkaliproofness. Therefore, this method cannot always be applied. One of the surface treatments of the copper conductor is to plate a low melting metal, such as tin, generally to a thickness of about 1 to 2μ. Another treatment is to use organic materials. Enamelling, for example, is comparatively cheap and commonly used. Experiments were carried out on wires treated with epoxy resin and polyvinylformal resin (45μ thick), which had a good sulfideproofness. The effects of a tinned wire and an enamelled wire lasted only for about three months and six months respectively. In case of metal plating, because of its thinness sulfides easily diffuse out through pinholes. Actually sulfide trees were observed in tinned wires. While an enamelled wire was more effective than a tinned wire, a technical problem in cable manufacture of application of enamelled wires to stranded conductors and the exfoliation of enamel in a long use made it impossible to get a long stability.

As stated above, it is not an easy preventive method to treat copper conductors. It is, of course, the most important to eliminate sulfides from the cable routes.

Practically, however, we cannot precisely grasp why, how and where sulfides generate, particularly at the sea bottom. The most preventive and practicable method is to develop a cable sheath which can block the permeation of sulfides into the cable.

As is clear from the above, that is, sulfides easily permeate through conventional sheaths like PE or PVC, metallic sheath is greatly effective in preventing sulfides. Lead, aluminum or steel has been used as a metallic sheath and PE or PVC has been served over the metallic sheath as an anti-corrosive layer. They are CLEZ (Crosslinked polyethylene insulated, lead sheathed and polyethylene served cable), CAVZ (Crosslinked polyethylene insulated, aluminum sheathed and PVC served cable), or CVKXVZ (Crosslinked polyethylene insulated, PVC sheathed, corrugated steel plate armored and PVC served cable). Hitherto these cables have been installed as waterproof, oilproof, chemicalproof and termite- or rodent-repellent cables. The metallic sheathed cables can block any sulfides and entirely prevent sulfide trees.

Of many preventive methods of sulfide trees, the metallic sheath alone remains effective for a long time.

4-3 Necessity of Sulfide Capture Cable

As previously mentioned, the sulfide trees are blocked by metallic sheath, which, however, cannot be applied to all the cables. The first reason is that the metallic sheathed cable has some demerits as follows. (1) High cost, (2) Heavy weight, (3) Difficulty in installation, and (4) Large overall diameter. It is practicable to use the metallic sheathed cable only at a place where large amounts of chemicals and water are observed before cable installation, but it is not economical to lay the cable where sulfides or other chemicals are not likely to generate or permeate. We can hardly foresee whether the sulfides will generate in 10 years' time or more. For instance, in the route of a submarine cable it is difficult to detect sulfide generation beforehand; in a directly buried cable route it is hard to know when the sulfides will generate and permeate. Therefore, a new preventive method must be developed, which is not economically disadvantageous, even if no sulfides generate or permeate. That is, there is a need of a cable less costly than a metallic sheathed cable, though a little higher priced than conventional cables, that has a simple construction to prevent sulfide permeation completely. If the cable is more resistant to chemicals and water, it is all the more desirable. The fact is that such a cable is required by users.

5. PRINCIPLE OF SULFIDE CAPTURE CABLE

5-1 Mechanism of Sulfide Capture

Generally, sulfides are reactive. By utilizing the chemical reaction, active sulfides can be transformed into a stable compound. Thus, it is an effective prevention to change the sulfides into a stable compound before they reach to the copper conductor. Sulfide capture plastics added with sulfide trapping agent to form a stable compound by reaction with the sulfides has been developed. The sulfide capture reaction is

$$S^{--} + M^{++} \longrightarrow MS$$

where S^{--} is a sulfide invading from the outside, M^{++} is a compound added to plastics to react with a sulfide (Sulfide trapping agent). And MS denotes a stable compound. For causing such a reaction and for trapping sulfides effectively, the following conditions should be required:

(A) As basic plastics,

(1) Low permeability of water and chemicals. This is desirable since the sulfides often dissolve in water and come into cables with water.

(2) Excellent compatibility with the sulfide trapping agent.

(3) Keeping excellent physical properties, especially mechanical and low temperature properties, after the admixture of the sulfide trapping agent.

(4) Low cost.

(B) As sulfide trapping agent

(1) Water-insolubility before and after the reaction with the sulfides.

(2) Long-term stability before and after the reaction with the sulfides.

(3) Excellent compatibility with the basic plastics establishing uniform dispersion.

(4) Fast reaction with the sulfides.

From many screening experiments on materials, it is found that polyolefin plastics as basic plastics and metal compound as sulfide trapping agent are suitable. Thus, the protective layer composed of sulfide capture plastics can transform the sulfide invading from the outside into a stable compound.

5-2 Sulfide Capture Function

Sulfide capture ability is illustrated with the following examples:

Low-density PE (MI 0.3, density 0.92) is mixed with 40 (phr) trapping agent B and blended by a roll to disperse trapping agent B uniformly in the PE, which forms a pure-white sulfide capture plastics. This plastics is molded to 12 mm ϕ elliptic rod and immersed in H_2S saturated water, it gradually turns into black from

the outer layer (Photo. 8), as the sulfides permeate into the plastics and black metal sulfide is produced by reaction of H_2S and trapping agent. The interface between

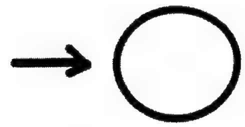


Photo. 8. Blackened Layer Trapping Sulfide

blackened and white layers is clear observed and the blackened layer appears in uniform thickness. This result shows that the sulfides are completely trapped. By reducing the amount of trapping agent B, the thickness of the blackened layer is become larger than that shown in Photo. 8. If increased, it is smaller. Further, when plasticized polyvinylchloride is used as basic plastics, which has a higher water-permiability than low-density PE, the thickness of the blackened layer is larger (Fig. 3). And when high-density PE with a lower water-permiability is used, it becomes smaller even with the addition of the same amount of trapping agent.

The ability to capture sulfides depends upon the types of basic polymers, and the types and the amount of the trapping agents. Therefore, the combination of basic polymer with low water-permeability and adequate sulfide trapping agent can establish a perfect prevention of sulfides. However, the quantity of sulfide trapping agent is limited to maintain the mechanical strength of the plastics. Besides the problem may occur if the sulfide capture ability is lost after sulfide trapping agent runs out through reaction with sulfides. This problem, however, can be solved by a peculiar phenomenon of synergism in sulfide capture.

5-3 Synergistic Effect of Sulfide Capture

The phenomenon of synergistic affect of sulfide capture is briefly explained in the following. Once the layer trapping sulfide reaches a certain thickness in the sulfide capture plastics, no more the layer trapping sulfide is formed preventing sulfides permeation even if there exist sulfides in the environment. Generally in the amorphous part of crystalline polymer such as PE, sulfides are diffused. Particle sulfide trapping agent is added to PE and it almost concentrates on the amorphous part to make diffusion constant still lower. Then the trapping agent is combined with sulfur ion and changes the chemical construction. Following this, the layer trapping sulfide is closely packed and makes the diffusion constant even much lower. This synergistic effect of sulfide capture is displayed in a comparatively thin the layer trapping sulfide if a large quantity of trapping agent is loaded.

Photo. 9 shows the synergistic effect of sulfide capture. As seen from it, about 1.5 mm thick layer trapping sulfide is formed (black part) after the immersion in H_2S saturated water for 30 days and the thickness has not been increased and kept almost the same after 360 days' immersion. This indicates that the synergistic effect of

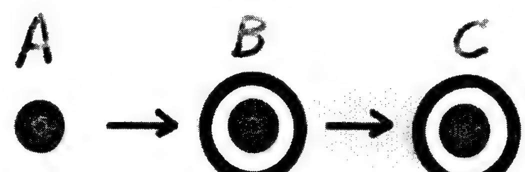


Photo. 9. Synergistic Effect of Sulfide Capture Layer

sulfide capture is performed. It is shown in Fig. 3. The permeation distance given in it means the thickness of the layer trapping sulfide. In case of PE base, its thickness of the layer trapping sulfide reaches a fixed value in a short immersion time.

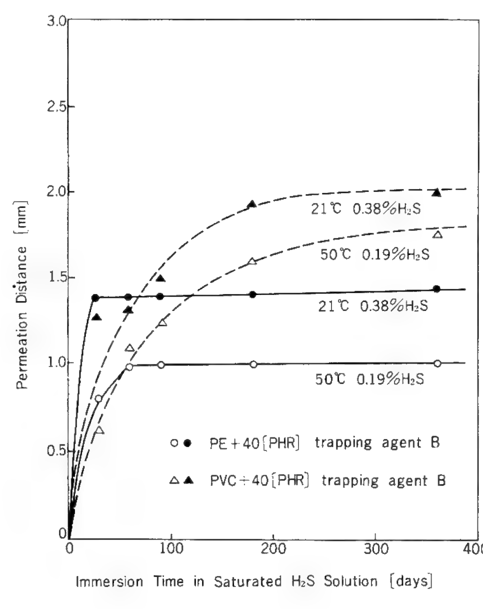


Fig. 3. Synergistic Effect of Sulfide Capture Plastics

So far, the sulfide capture ability can be increased by the synergistic effect. And the sulfide capture plastics can work as a perfect prevention of sulfides permeation when it is applied as a protective layer of

cable in a certain thickness.

5-4 Confirmation of Sulfide Capture Effect

The principle of the effect previously mentioned was confirmed with the cable construction in the following. Photo. 10 is a magnified photograph of the cross-section of the experimental cable, of which construction is a 3 mm thick white sulfide capture layer over a 1 mm thick PE insulation. This cable was submerged in water saturated with H_2S at 21°C for one year with its terminations sealed. As seen in Photo. 10, half of the sulfide capture layer turned into black, which looked as if two layers had been extruded. The characteristic patterns

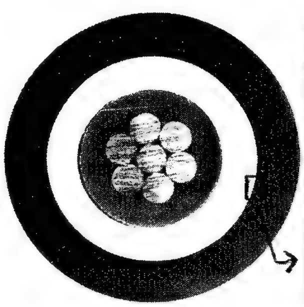


Photo. 10. Cross-section of Model Cable

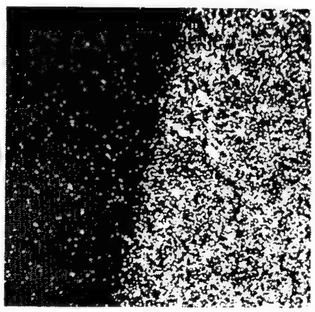


Photo. 11. Existence of Sulfur at the Interface

of X-rays of sulfur (S) were measured at the interface between the black and white layer by X-ray microanalyzer. The results are shown in Photo. 11, in which white specks show the existence of sulfur. It is evident that there is much sulfur at the black layer trapping sulfide, while no existence of sulfur is observed at white layer. (Some specks are not sulfur but background.) Further, the copper conductor of this cable did not change in color, which proves that sulfides did not permeate to the conductor at all. As proved by these results, the sulfide capture layer has a perfect protection against of sulfides permeating from the outside.

5-5 Property of Sulfide Capture Plastics

As previously mentioned, the sulfide capture plastics contains considerable amount of metal compounds. Naturally it should satisfy the requirement as cable materials. The physical, chemical and processing properties before and after trapping sulfides will be described.

5-5-1 Physical properties Fig. 4 shows the specific gravity of PE (density 0.92, MI 0.3) mixed with trapping agent A and trapping agent B. Fig. 5 shows the properties of low temperature brittleness and tensile elongation of PE (density 0.92, MI 0.3) mixed with trapping agent B.

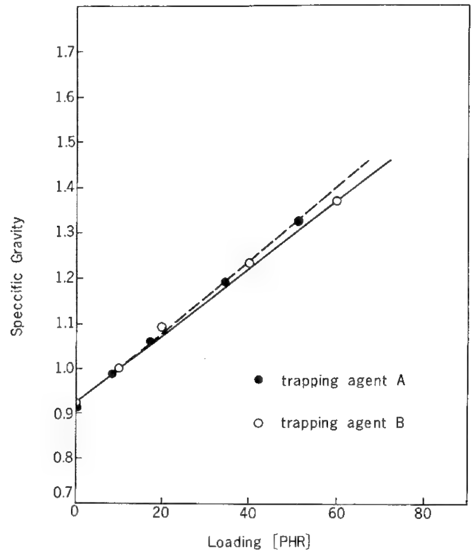


Fig. 4. Specific Gravity of Sulfide Capture Plastics

Brittleness temperature goes up by 20°C when 60 (phr) trapping agent B is loaded. But the sample, which formed the layer trapping sulfide by reacting all the loadings with H_2S, has the same excellent low temperature brittleness property as the original. The tensile elongation is kept same even if 60 (phr) is loaded.

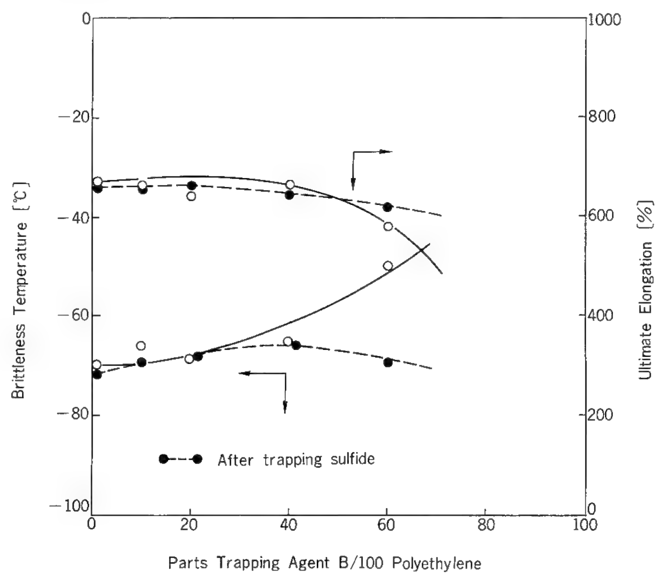


Fig. 5. Brittleness Temperature and Elongation of Sulfide Capture Plastics

In regard to environmental stress cracking, each compound, which is illustrated in Fig. 5, was tested in accordance with ASTM-D-1963-60T Method, but no cracking was observed after 10,000 hours.

5-5-2 Chemical Property Figs. 6 and 7 illustrate the

ageing properties of PE (density 0.92, MI 0.3) mixed with trapping agent B. As is clear from the data, the retentions of tensile strength and elongation are over 80% of

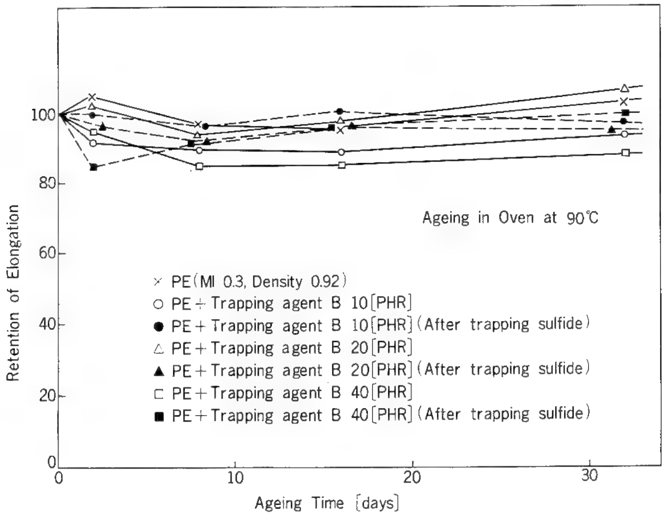


Fig. 6. Ageing Property of Elongation of Sulfide Capture Plastics

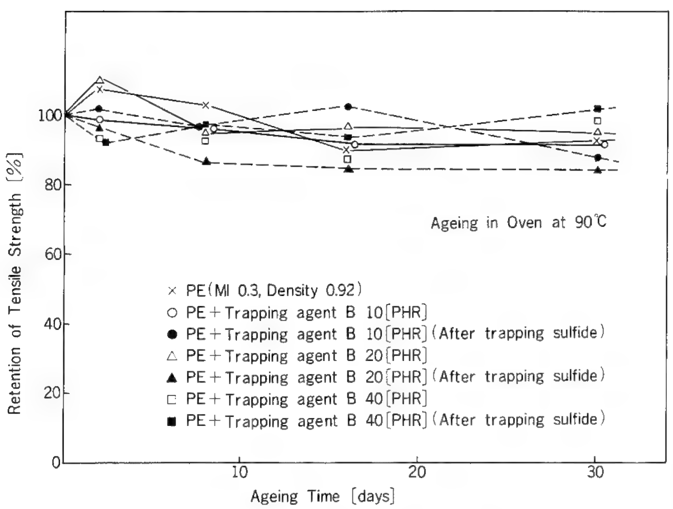


Fig. 7. Ageing Property of Strength of Sulfide Capture Plastics

the original value. Fig. 8 shows the retension of elongation when samples are immersed in many kinds of chemicals. The sulfide capture plastics is a little superior to the original PE in chemical resistivity. It is further improved when a layer trapping sulfide is formed and the plastics becomes more closely packed.

The characteristic that the sulfide capture plastics resists not only sulfide but also general chemicals is a great advantage of the cable.

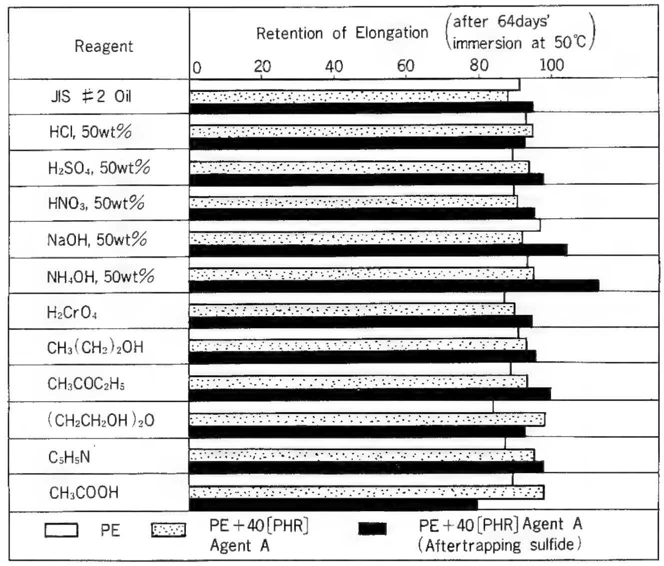


Fig. 8. Chemicalproofness of Sulfide Capture Plastics

5-5-3 Processing Property Fig. 9 shows the processability of the sulfide capture plastics. When PE is mixed with trapping agent B, the melt viscosity decreases and makes processing easy.

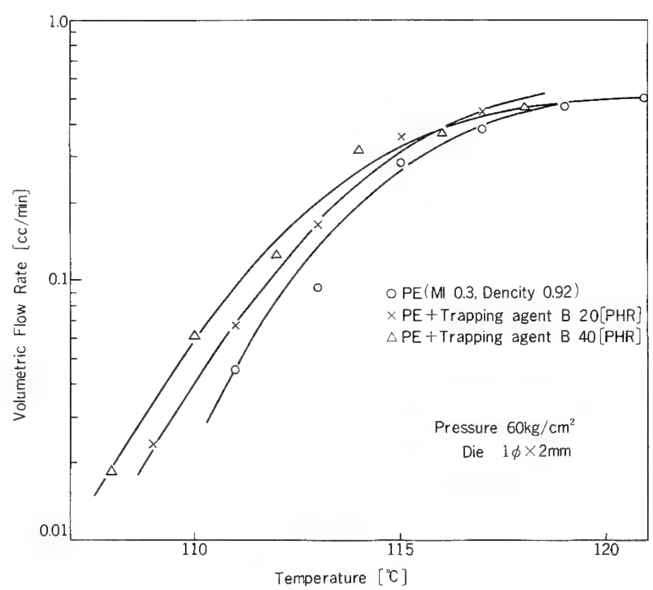


Fig. 9. Processability of Sulfide Capture Plastics

In case of loading 40 (phr) trapping agent B in PE, the compound could be extruded at the temperature 10°C lower than the original PE with smooth surface.

It is concluded that the sulfide capture plastics can have the sufficient function as cable materials in physical, chemical and processing properties. Especially, it is noticeable that the properties are improved after

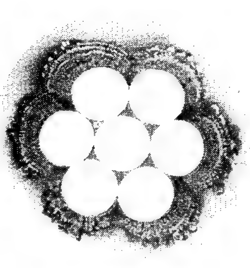
trapping sulfide.

6. APPLICATION OF SULFIDE CAPTURE CABLE

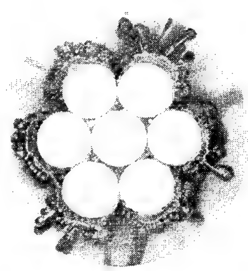
The problems incidental to the application of the sulfide capture plastics to a cable are investigated below. The sulfide capture cable is called as NS cable (Non-Sulfides Cable) hereinafter.(8)

6-1 Effect of Sulfide Capture on Cable

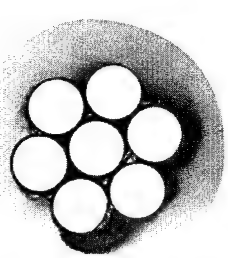
As experiment for one year was performed on a model cable, of which construction is a 3 mm thick white sulfide capture layer over a 1 mm thick PE insulation. For comparison, bare (non-treated), tin plated and enamelled copper conductor, a 1 mm thick PE insulated wires were also tested in H_2S saturated water. The result on its insulation resistance (Fig. 10) and 6-month growth of sulfide tree (Photo. 12) are reported here. In Fig. 10, the insulation resistance is not reduced in NS cable, while it remarkably decreases in other wires. As seen in Photo. 12, no sulfide tree is observed in NS cable, but many trees are growing in a bare wire and tin plated wire, and in an enamelled wire trees are found locally. The experimental results prove that the NS cable has perfect long-term sulfide capture ability after immersion in a highly sulfides concentrated water.



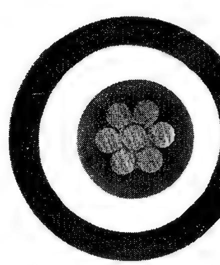
Non-Treated Wire



Tin Plated Wire



Enamelled Wire



NS Cable

Photo. 12. 6-Month Growth of Sulfide Tree

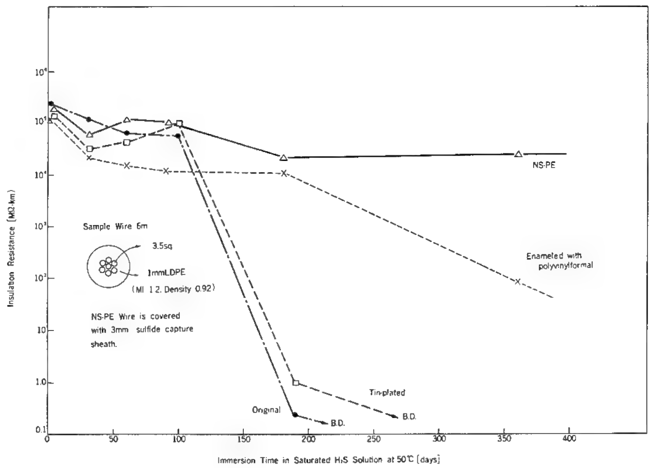


Fig. 10. Insulation Resistance of NS Cable

6-2 Construction of NS Cable

It does not matter in principle where the sulfide capture layer is extruded on the conductor, but it is recommended that the layer should be over the insulation, combined with a PE sheath so as to have a double-jacket construction (Fig. 11). This construction increases the

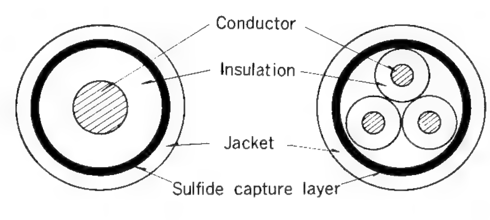


Fig. 11. Construction of NS Cable

mechanical resistance in installation and its chemical-proofness as compared with a single-jacket cable like conventional PE sheathed or PVC sheathed cable. The reason why its chemicalproofness is increased is as follows. Of widely employed polymers for cable materials, such as PE, PVC, chloroprene, butyl rubber, and ethylene-propylene rubber, PE is the most excellent in chemicalproofness, because there are only a limited number of dissolvents of PE in general use, such as carbon tetrachloride, trichloroethylene, benzen, chloroform, carbon disulfide, oils and nitric acid and the like. But, while good chemicalproof, non-filled PE is used for the sheath, it occasionally allows water and sulfides to permeate easily. Therefore, in the NS cable, a double jacket type was used to afford complete prevention from water or sulfide penetration by means of "outer PE layer" and "inner sulfide capture layer." In other words, the outer layer checks the greater part of the incoming chemicals, while, on the other hand, the inner sulfide

capture layer prevents the penetration of any chemicals, as sulfide, that may have permeated through the outer layer. As described before, besides trapping sulfides completely, this sulfide capture layer can prevent water and chemicals permeation since it is a filled type. Against the chemicals dissolving PE, the double jacket controls the dissolution time, and the chemicalproofness of the layer is additionally expected as shown in Fig. 8. By developing the double-jacket construction, a very tough cable has been manufactured.

6-3 Application of NS Cable to Practical Service

Based on these experimental results, we have introduced the NS cable into practical use. Before practical application, many field tests were repeated for long period of time. Photo. 13 shows the experimental use of the NS control cable at a petrochemical plant in a polluted district. After 13 months' installation, the NS

Photo. 13. Experimental Use of NS Cable

Cable (600 V, 3 x 3.5 mm^2) developed no troubles. In heat cycle experiments in water, no failure was observed.

Photo. 14. Various NS Cable for Practical Service

Such field tests were carried out repeatedly at various places with satisfactory results. Now the NS cable is used for control cable, power cable and submarine cable. Photo. 14 shows practically applied control cable, submarine cable and crosslinked PE insulated submarine power cable. Photo. 15 shows the installation of the NS power cable (6 KV, 3 x 250 mm^2).

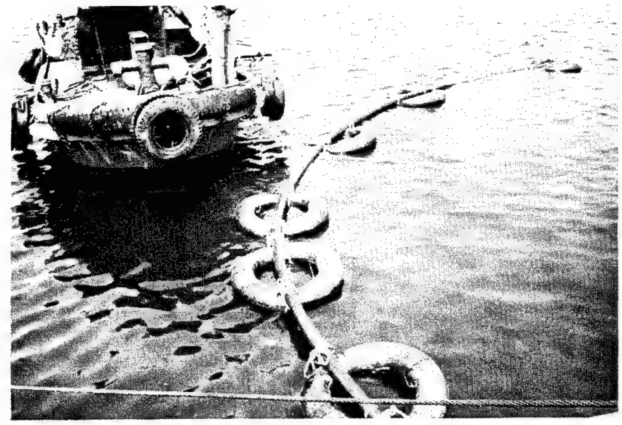


Photo. 15. Installation of NS Power Cable

7. CHARACTERISTICS OF NS CABLE

The characteristics of the NS cable will be summarized here. First of all, a comparison between the NS cable and other chemical-resistant cable on the construction, physical and chemical properties, price and other points is shown in Table 3. As the values vary by

Table 3. Comparison of Properties of Various Chemicals-Resistant Control Cables

Item \ Cables			E E	NS-EE	EKXEZ	ELEZ
Construction	Insulation		PE	PE	PE	PE
	Specific sheath		—	Plastic sulfide capture sheath	Corrugated steel	Lead
	Protective jacket		PE	PE	PE	PE
	Outer diameter	(%)	100	113	174	129
	Weight	(%)	100	120	256	302
Physical properties	Maximum service temperature	(°C)	75	75	75	75
	Bending diameter	(%)	100	113	303	226
	Handling		Easy	Easy	Difficult	Difficult
	End treatment		Easy	Easy	Very difficult	Difficult
Chemical properties	Coldproofness		Excellent	Excellent	Excellent	Excellent
	Waterproofness		Good	Better	Excellent	Excellent
	Sulfide resistance		Unsatisfactory	Excellent	Excellent	Excellent
	Oil resistance		Good	Better	Excellent	Excellent
	Other chemicals resistance		Good	Better	Excellent	Excellent
	Fire retardancy		Good	Good	Excellent	Excellent
	Termite repellency		Not good*	Not good*	Excellent	Excellent
	Rodent repellency		Not good*	Not good*	Excellent	Excellent
Price			100	111	212	164

* Becomes good if repellent is added to PE sheath

cable size, a 2 mm^2 (equal to AWG #4), 9-core control cable is chosen as an example. The characteristics of the NS cable are as follows:

(1) Complete prevention of sulfide trees.

It is confirmed from many results that the NS cable can completely prevent sulfides from permeating.

(2) Excellent chemicalproofness.

As compared with conventional PE sheath, the double jacket better prevents chemical permeation and the reduction of mechanical property due to chemical swelling. The combination of non-filled PE at the outer layer and the filled sulfide capture layer improves chemicalproofness significantly.

(3) Reduction in cable weight.

The NS cable is very light because of no metallic sheath. The specific gravity of its sulfide capture layer is 1.5 or less, which is much smaller than 11.3 of lead. As seen from Table 3, the weight is $\frac{1}{2}$ or less than that of a corrugated steel plate armored cable and $\frac{1}{2.5}$ of that of a lead sheathed cable.

(4) Good flexibility.

The NS cable has a better flexibility than the metallic sheathed cable, since the sulfide capture layer is of plastics. Table 3 shows that the NS cable has a smaller overall diameter and a smaller bending radius than the corrugated steel plate armored cable or lead sheathed cable: the bending radius is $\frac{1}{2}$ or less of the latter and $\frac{1}{3}$ of the former. Thus, the NS cable has an excellent bending property.

(5) Ease of handling.

Because of its light weight and good flexibility, the NS cable is easily installed. In addition, its jointing and terminal treatments are very easy and simple, as compared with the metallic sheathed cable. Cutting and processing of the sulfide capture layer can be made by the same method as for conventional PE.

(6) Stability in manufacture.

The sulfide capture layer is easily formed by extrusion, and voids and unequal thickness of the layer are rarely produced. A considerably large length can be manufactured in uniform quality without any joint.

(7) Economical

The NS cable is of low cost having the superior properties. The cost is about $\frac{1}{2}$ of that of corrugated steel plate armored cable and $\frac{1}{1.5}$ of lead sheathed cable. The chemicalproof effect of the NS cable comes between conventional plastic jacketed cable and metallic sheathed cable, and it is equivalent to the metallic sheathed cable in sulfide capturing effect; it is easier to handle and more economical. These are advantages to cable users.

8. USAGE OF NS CABLE

In this chapter, polluted environment and the recommendation of type of the NS cable, where the cable should be installed, are discribed.

8-1 Present Environmental Pollution due to Sulfides at Cable Installation Place

In addition to the example given in Paragraph 3, the deterioration of cables caused by sulfide trees was observed in Japan: the troubles were reported with 600V PE insulated and PVC sheathed control cable (10 x 3.5 mm^2) in the ammonium sulfide plant and 600V crosslinked PE insulated and PVC sheathed power cable (3 x 8 mm^2) in the trough at a petroleum plant.(9) (10) Further, the faults of a PE insulated and PE sheathed telephone cable due to sulfide growth on the core(11) and sulfide trees of 6KV crosslinked PE insulated, PVC sheathed and double steel wire armored power cable (3 x 14 mm^2) were reported.(12) In the United States, the growth of sulfide trees was observed in a cable in operation installed on the West Coast.(13) Thus, cable deterioration by sulfides sometimes occurs, but it is difficult to detect the growth early enough. At a reclaimed land or in a chemical plant area, sulfate and sulfite compounds are reduced to H_2S by bacteria in the ground. At the sea bottom, seaweed grows H_2S by the work of bacteria. In a volcanic zone or a hot spring area, sulfides are usually thought to be existing. The distribution of sulfides in and around the cable installed has been investigated by us for these two years, using "S-tector" developed by us, which is a quantitative detector of sulfide accumulation over a long period, and it was confirmed that sulfides existed at many places; the results will be reported in other papers. It is, therefore, advisable to take preventive measures against deterioration by sulfides before a cable is direct buried.

8-2 Applications of NS Cable

The NS cable can be effectively used the following cables:

(1) Cable in a trough or direct buried at chemical plants.

(2) Cable direct buried at petroleum refineries.

(3) Cable in a trough or direct buried at reclaimed lands.

(4) Submarine cable.

(5) Cable for hot spring districts or volcanic zones and cable for hydrothermal power plants.

Especially where the submergence by water along the cable route is suspected, the NS cable is recom-

mended.

The NS cable is suitable for the construction of the following cables:

(1) Control cable.

(2) Low voltage power cable.

(3) Submarine cable.

(4) Transmission cable without metallic sheath, such as polyethylene insulated pair city cable.

9. CONCLUSION

A new type of deterioration has been found which may adversely affect plastic insulated cables. This phenomenon is that sulfides permeating through the sheath and the insulation from the outside of the cable finally reach the copper conductor to form cuprous sulfide by the reaction with copper. Cuprous sulfide crystallines in the insulation in the form of bushlike or treelike deposits; this is termed "sulfide trees". The NS cable was developed as being the most effective in the prevention of sulfides, by the use of a sulfide capture layer consisting of sulfide capture plastics under the PE sheath. On account of this double-jacket construction the cable excels in the following points:

(1) It can block sulfides as completely as a metallic sheathed cable, and has also an excellent resistivity to other chemicals.

(2) Composed of plastics, it is light in weight and flexible for easy handling.

(3) It is very low in cost and economical.

It may be concluded that the NS cable is quite a new type of cable which is the most suitable for control cable, low-voltage power cable, submarine cable and telephone cable buried underground at chemical plants, petroleum refineries, reclaimed lands and for underwater installation.

10. ACKNOWLEDGEMENT

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PROTECTING COMMUNICATIONS CABLES FROM RODENT ATTACK

by
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Summary

Providing uninterrupted service to telephone customers is an almost impossible task in certain geographic locations because of animal attacks on cable. This paper deals with two of our adversaries, the squirrel and gopher. These animals cause severe damage to many miles of telephone plant each year.

In an effort to prevent these attacks, various cable constructions have been tried, but in all cases some part of the cable is penetrated by these animals voracious bite. Because they can cause some degree of damage to any practical cable construction, and they very often gnaw on any cable they come to, the solution is to prevent cable attacks by keeping these animals away from the cable. A chemical repellent system appeared to be one method that could be used. The discovery of such a product, or products would afford not only protection of cables, but of cable accessories as well.

Recognizing this need, we initiated a project to evaluate available repellent compounds for cable protection. The evaluation began in 1969 and is of a continuing nature so that we can evaluate long term as well as initial effectiveness. The test consists of cables both treated and untreated that were installed in areas of high squirrel and gopher infestation. Because the cables were placed using standard installation methods, this paper is a report of practical aspects of applying chemical repellents and a review of their capabilities.

At the time of this writing, the rodent activity in both the Iowa squirrel test sites and the Minnesota gopher test sites seems to have stabilized and we have definite recommendations to make.

Introduction

Establishing effective circuits between the telephone office and the subscriber has always been a prime concern of the telephone companies. In the early days, a "usable" circuit was all that was expected. These circuits were provided by stringing uninsulated wire from pole to pole. As the demand for more and better service increased, the open wire, as it came to be known, was replaced with communication cables. These cables provided several advantages over open wire. One of the most important was constantly dry conductors. During rain storms open wire circuits became noisy, especially when wet branches bridged the wires. Cable was not so affected by water and a new level of transmission quality was established. However, the cable jacket that helped to provide the improvement in service also proved to be a hindrance under certain conditions. It was quite an effective raincoat until punctured at which time it became an excellent reservoir. Water would enter the hole, migrate in the core and settle in low places in the cable. In extreme cases it could even fill entire lengths. Under these conditions we would be fortunate to have even "usable" circuits.

Obviously, there are many different ways in which a cable jacket can be damaged. In this text we shall concern ourselves with damage inflicted by gnawing rodents, both in buried and aerial plant.

History

Most of the rodent damage to buried cables can be attributed to the gopher, a small burrowing creature that has a strong propensity to use his large incisor teeth on any object which happens to be in his path. In the past, the basic approach to buried cable protection has been to incorporate heavy metallic shielding into the cable. Shielding materials included copper, brass, copper/steel laminates, and steel. Although these shields decreased the amount of damage inflicted upon the cable core; they could not prevent punctures to the jacket, since it is extruded over the shield. Furthermore, they did not always prevent conductor damage. In locations where gopher damage was particularly severe, existing cables have been replaced with steel tape armored cables. This type of remedial action provided adequate gopher protection, but requires the telephone company to incur the expense of placing two cables to get one working unit or to invest large sums of money to install expensive armored cables in all locations initially. However, although these armored or heavily shielded cables stop the gopher after jacket penetration, the hole he gnaws leaves the bare metal to be corroded and an electrical path to ground. The corrosion we can not live with, but the ground path is useful as it provides a method of detecting the location of cable

trouble inflicted by the pesky rodent.

We have a similar problem with our aerial adversary, the squirrel. He is equally as unpredictable as the gopher and can inflict equally severe damage. In the past one method of providing aerial cable protection was the use of armored cables designed for direct burial. More common was the placement of protective guards over standard aerial cable. This method provides adequate protection in areas where guards are placed; however, placement can not usually be decided upon until after the original cable is damaged. Furthermore, once the guards are placed, the little animal may very well move down the span and attack the cable at a new location. Obviously, it would be impractical and expensive to place guards on entire spans of cable.

Squirrels Walk the Treated Cable,but Do Not Gnaw It

These practices have been used because they appeared to be the best available methods of keeping the subscriber in service. However, they have been objected to because of their lack of effectiveness and practicality and the significant increase of in-plant cost. An obvious necessity was a less expensive, more effective method of protection so that cable could be protected before damage occurred. One such possibility, the use of repellent compounds appeared promising, and a study was initiated to determine their merit.

Our investigation into the use of repellent compounds for cable protection began in 1969. This type product was relatively new, so we formulated a program that was more than a routine capability evaluation. The study was arranged also to provide information as to the side effects the repellents might have on people, cable accessories, and to develop methods for applying and handling the products.

At the outset of this project, only two products were commercially available. The manufacturers' of these products were contacted and a joint study was begun so that we might determine the capability of the products to protect aerial and buried telephone cables. The companies, Phillips Petroleum and M & T Chemicals each make a basic repellent concentrate that is diluted in the field before application. Phillips' repellent can also be incorporated into a jacketing plastic.

Recommendations

The program, when completed, proved quite fruitful. We evaluated our data and were able to develop methods of handling and applying the materials. As a result of this study we can recommend the use of certain repellents for specific applications as follows:

> Buried Installations: Treat the soil surrounding the cable during installation with Phillips Petroleum Co. "R-55" repellent compound. (See recommended procedure details elsewhere in this article.
>
> Aerial Installations: Coat installed cables in squirrel infested areas with Phillips Petroleum Co. "R-55", or M & T Chemicals "Bio Met 12" repellent. (See recommended procedure details elsewhere in this article.)

Our recommendation of repellents suitable for the cable protection application indicated are based on two factors.

1. The products chosen are relatively safe to use and do not have undesirable side effects on the cable or accessories.

2. Final approval of acceptable products was made on the basis of success in protecting installed cables. The success was determined by monitoring the number of attacks on the cables in our test sites. These inspections revealed that we had 100% success in preventing jacket penetration of aerial cable with both products. In the buried installation, however, we had severe damage to the Bio Met 12 treated samples. The Phillips treated samples were much more effectively protected. Only two of these samples had jacket punctures, one of which involved conductor damage. It is important to note that the total footage damaged was less than 3% of the Phillips protected cable.

Application Methods

Both of the repellents evaluated can be applied in the field or during manufacturing. All things considered, the best time to employ these deterrents is during field installation. The reasoning behind this choice is that with exposure to the elements, the products lose strength. If added to the cable during manufacturing, the repellent in or on the cable jacket will lose potency during storage and transportation and be placed in plant with something less than 100% effectiveness. So to receive maximum benefit, treatment should be made in the field.

Besides providing less than 100% effectiveness at the time of installation, the manufacture of

treated cables would result in increased cost to the customer due to special manufacturing equipment and procedures. When jacketing with the special polyethylene, fumes are given off due to heating of the compound. To keep these fumes clear of the work area it would be necessary to install ventilation systems. Another special procedure would be the change over from normal jacketing plastic to the repellent plastic. Typically, one type of plastic is fed to the extruders through a bulk vacuum system. The use of repellent plastic would require a special delivery system to supply the plastic to the extruder without contaminating normal jacketing plastic. When the run was complete, the extruder would have to be bled and all tooling cleaned. The costs of these operations could be absorbed in large orders for cable, but because the product would be a special order these costs could not be absorbed quickly and the product would be quite expensive.

The other possible method of factory treatment is to coat standard cables with a solution of repellent compound and force dry it. This method would involve more expense than jacketing with repellent plastic because a whole new manufacturing line would be necessary. Again a special ventilation system would be a must. Field installation would avoid these ventilation problems.

Recommended Application Methods

Field application of the repellents is a simple matter and sophisticated equipment is not required. In fact, our application equipment for buried cable was quite crude as compared to the metering pump now available from Phillips, and even it is an uncomplicated device. Aerial application requires only a paint brush. From our experience, each category of plant has its own optimum application method.

Method for Buried Application: The soil surrounding the cable should be treated through the use of a spray head mounted on the cable plow chute where the cable exits. The repellent is metered by a pump that is actuated when the plow is moving. Trenched sections should be sprayed with a tank type garden sprayer. Manual spraying requires care on the part of the person applying the repellent to assure proper saturation of the ground. When applying these repellents under pressure, care must be exercised so that the repellent does not contact skin or eyes. A direct spray on the skin causes immediate irritation.

Method for Aerial Application: Aerial cable should be treated after it is installed. The application can be made by spraying or brushing; however, we do not recommend spraying because of the dangers of the repellent drifting with the wind. Brush application is much safer and most easily done from a bucket truck. If a cable car must be used, the person brushing the repellent should wear a plastic or rubber apron to protect himself from dripping repellent. During all applications, personnel should wear plastic or rubber gloves and eye protection.

In areas where trees are very dense, it is uneconomical to treat the cables due to the high cost of tree trimming prior to application of the repellent. To protect these spans it is usually more economical to place mechanical guards on the cable.

Field Trials

Our field trials were to be a very important part of our evaluation, so several locations were carefully considered. After making field trips to several locales, two separate test locations were chosen for installation of the test cables. One in Ft. Dodge, Iowa for squirrels and the other in Minnesota for gophers. The Minnesota test site is in the Sherburne National Wildlife Refuge, a preserve comprising over 31,000 acres. Preservation and study of waterfowl is the major activity at Sherburne, however, judging from the appearance of some of our test installation samples, the gophers are taking over. Each of these two test locations consist of three sets of five cables. The cables are 25 pair, 22 Awg Alpeth-FPA prepared for installation as described:

1. Control - Standard construction ALP-FPA cable was used for reference purposes. This construction was chosen because the jacket and shield are relatively easy to penetrate.

2. Bio Met 12 Factory Treatment - Standard construction ALP-FPA cable was coated with Bio Met 12 and force dried in the factory.

3. Bio Met 12 Field Treatment - Standard construction ALP-FPA cable. The earth surrounding the cable was sprayed with Bio Met 12 as the cable was plowed. Aerial cables were brush coated.

4. Phillips J551 - Standard construction ALP-FPA cable core was jacketed with this high density jacketing resin containing "R-55" repellent.

5. Phillips "R-55" Field Treatment - Standard construction ALP-FPA cable. The earth surrounding the cable was sprayed with "R-55" as the cable was plowed. Aerial cables were brush coated.

Buried Installation: (Minnesota)

The buried installation was made in the ditches parallel to a sand road. Gopher activity is very high in this location. Mounds appear so frequently that it is difficult to walk through the area without stepping on them. The cables were plowed using a Vermeer vibratory plow. Each cable is 200 feet long and placed at a depth of 24

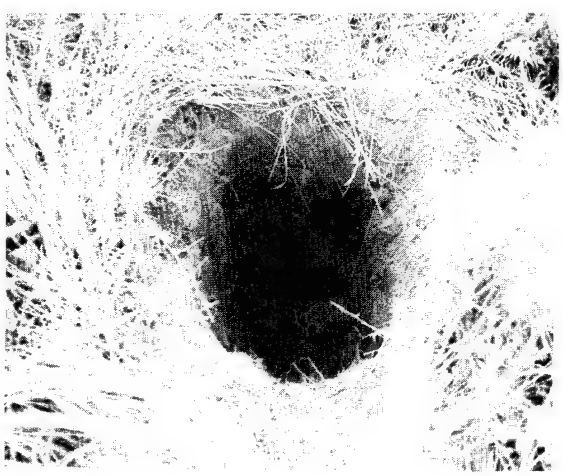
inches. All cables were plowed in series with ends in pedestals so that electrical testing could be conducted. Figure I shows the layout of the test site. As an added control feature, moisture plugs were installed in all cable ends. By having these plugs, we could establish that any water entrance into the cable could be attributed to jacket damage.

Record of Field Visits

August 25, 1969 - The test cables were plowed in and pedestals placed. All cables were checked for shield to earth grounds and none were found.

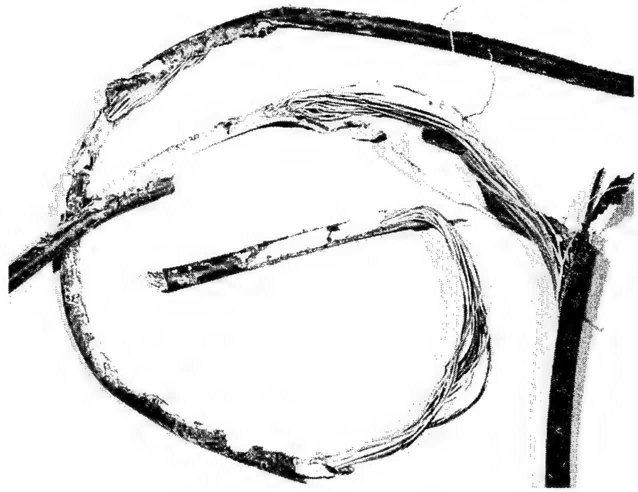
October 16, 1969 - The test site was revisited. Gophers were still working in the test area, but there were apparently no attacks on any of the cables. That is, they had not penetrated the jacket as no shield to earth grounds were found. For further evidence, the following electrical measurements were made: mutual capacitance, dissipation factor, continuity (ring, tip, shield), shield to earth grounds. No indication of any damage was found.

June 22, 1970 - Visible gopher activity was the same as it had appeared previously, fresh mounds were found throughout the test site. Again electrical measurements were made. This time cables were found to have been attacked by gophers. To determine the amount of activity, a count was taken of the attacked areas. To locate these areas a cable fault locator was used and each attack pin-pointed and recorded. To determine the extent of damage done to the cables, an inspection hole was dug at one damaged place of each attacked cable. To minimize the disturbance of the test, this hole was dug with a garden trowel and carefully back filled. Test holes were from six to ten inches in diameter and twenty-four inches deep.



A Typical Test Hole

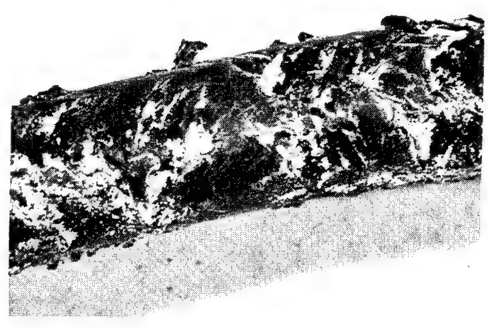
Samples protected with Bio Met 12 repellent were severely attacked. Both methods of application of "R-55" repellent (field and factory) proved to be much more successful. Only one of these Phillips protected cables had been attacked, and only in one place. The repellent had little effect on the gopher, as the cable was gnawed and the conductors cut for about six feet. All other "R-55" field treated and jacketed samples remained untouched. Because of the severe damage to the Bio Met 12 treated cables, they were abandoned.



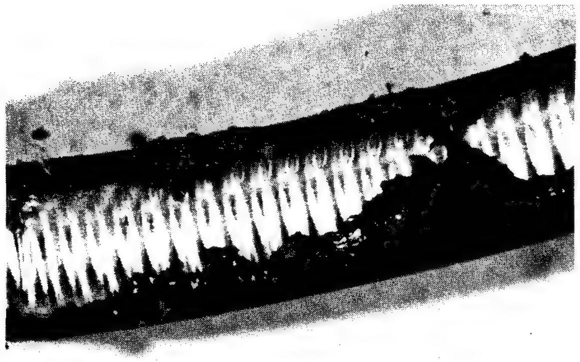
An Example of Severe Damage

June 21, 1971 - This test site was revisited. Gophers were still active in the area, however, there were no new attacks on the "R-55" field treated or repellent jacket cables.

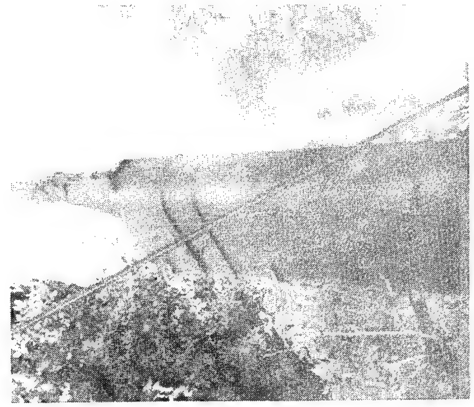
July 5, 1972 - This inspection revealed the first attack on a cable jacketed with plastic containing Phillips "R-55". No new attacks were found on any of the other Phillips protected cables. Attacks continued on all other samples. They can be classified into three categories; severe damage, tooth marks, and jacket and shield removed from the top of the cable.



Tooth Marks in the Jacket



Jacket and Shield Removed from Top of Cable



Attacks are Prevalent on Untreated Closures

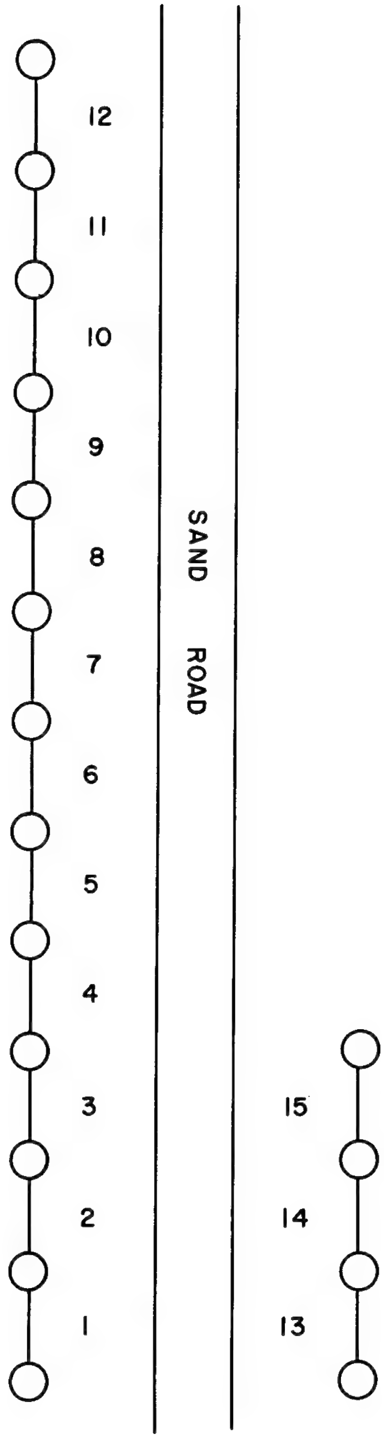
Aerial Installation: (Iowa)

The aerial installation was made on existing pole lines through areas of high squirrel infestation. Figure II shows the three test locations. In past years, the operating company has had many outages due to squirrel damage. Our cables for the test were placed parallel to the existing working cables except in one case where our test cables replaced a severely damaged working cable. These test cables are being used for local service. Working cables in the other two areas are two types. One area has a steel tape armored cable and the other has standard cable protected with cable guards. These methods of protection are effective but they are quite costly in comparison to treating the cable with a repellent compound.

The test cables were installed the first week of July, 1969 and were thoroughly inspected the first week of July for the two ensuing years. No jacket penetrations have been found, but there were slight tooth marks on the jacket in a few places. At the time of this writing a field visit had not been made, but reports from the field indicate that there have been no penetrations through the summer of 1972. Further evidence of the repellency of the products is provided by the ready access closures used on the test cables. These closures were not treated and have all been gnawed by the squirrels.

The best evidence of the adequacy of these repellent compounds is the section of working cable, as there have been no subscriber outages due to squirrel damage. Another important finding is that even though the repellent kept the squirrels from gnawing on the cable, it did not chase them from the area; so naturalists will not be offended by the telephone companies efforts to protect its plant.

This evaluation is a continuing one; we will be checking the cables periodically in an effort to determine the repellent's effective working life.

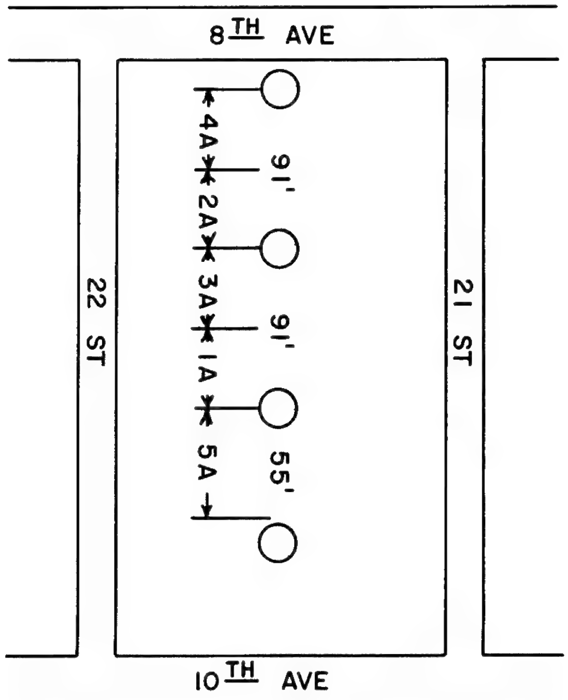


GOPHER TEST

200' per treatment--distance between pedestals

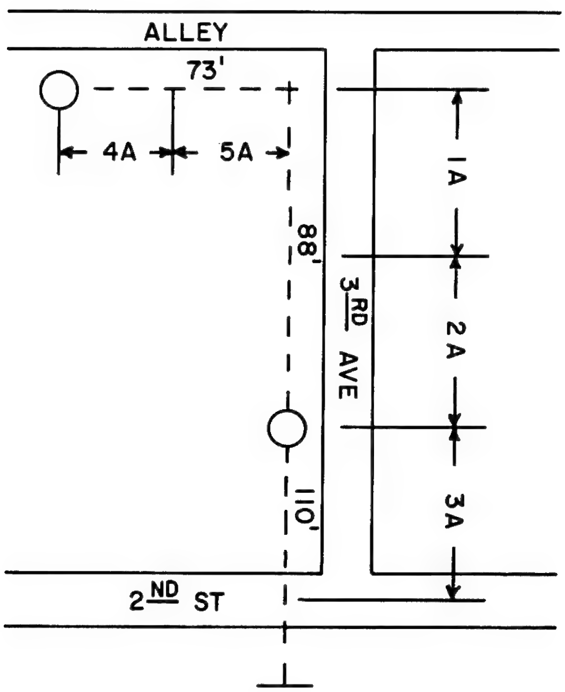
Position Number	Treatment	
1	3B	BioMet 12 Soil Treatment
2	5B	R-55 Soil Treatment
3	2B	BioMet 12 Coating
4	1B	Control
5	5B	R-55 Soil Treatment
6	4B	J-551
7	1B	Control
8	1B	Control
9	2B	BioMet 12 Coating
10	5B	R-55 Soil Treatment
11	4B	J-551
12	3B	BioMet 12 Soil Treatment
13	4B	J-551
14	3B	BioMet 12 Soil Treatment
15	2B	BioMet 12 Coating

FIGURE I



SQUIRREL TEST SITES

Code	Treatment
1A	Control
2A	BioMet 12 Coating
3A	BioMet 12 Soil Treatment
4A	J-551
5A	R-55 Soil Treatment



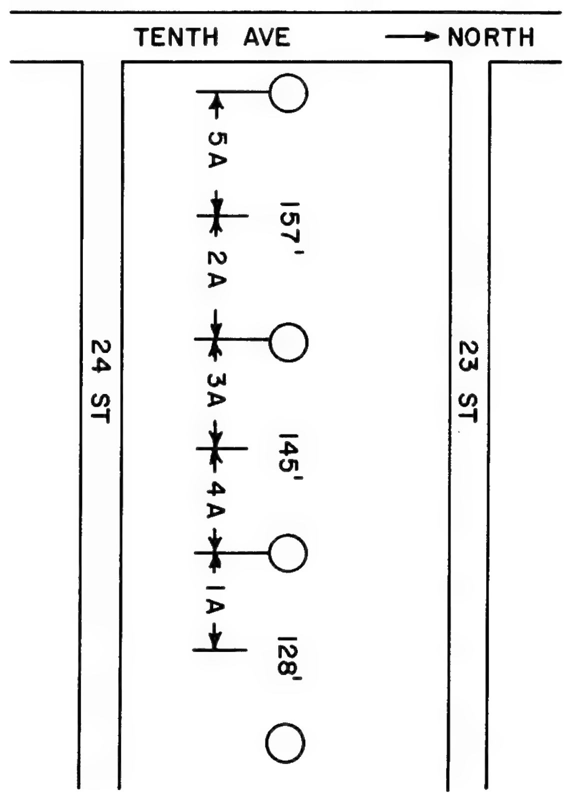


FIGURE II

John M. Lyon is Outside Plant Engineer for Anaconda Wire & Cable at the Communications Products Engineering Center, Sycamore, Illinois. Since joining the Company in 1964, he has been involved in all aspects of wire and cable development, manufacture, and application. Mr. Lyon holds a Bachelor of Science degree from Northern Illinois University where he studied Management and Industrial Technology.

EXAR®
A FLAME RESISTANT, HIGH TEMPERATURE, CROSS-LINKED WIRE INSULATION SYSTEM

N. Hildreth
Haveg Industries, Inc
Super Temp Wire Div.
Winooski, Vermont

J. Brooks
Haveg Industries, Inc
Super Temp Wire Div.
Winooski, Vermont

Summary

EXAR® is an irradiated cross-linked polymeric wire insulation that has been developed to fill the gap between present high and low temperature insulation. The distinguishing characteristics of EXAR are: outstanding heat resistance, flame resistance, is non-corrosive and is economical. EXAR motor lead wire passes an accelerated aging test at 250°C for six hours, is compatible with most varnishes and is both U.L. and C.S.A. listed as 125°C insulation.

EXAR hook-up and appliance wire meets the requirements of the U.L. FR-1 flame test, has excellent solder iron resistance and is U.L. listed in wall thicknesses of 1/32", 1/64" and 10 mils. EXAR is sold as a Mil Spec Hook-Up wire which meets the requirements of MIL-W-16878/B and /C.

Introduction

For many years the wire industry has worked to upgrade the high temperature performance of low-cost insulating materials. One technique that has been developed is cross-linking by irradiation. Introduced 18 years ago, the irradiation process is a simple one. After the thermoplastic compound is extruded onto wire, it is exposed to high energy electrons from an electron accelerator. The energy from the fast moving electrons is intense enough to change the chemical structure of many materials. In a properly formulated polymer system this change can cause extensive cross-linking and even change a thermoplastic to an insoluble, infusible thermosetting plastic.

For instance, a paper presented at the 18th International Wire & Cable Symposium showed that irradiation cross-linked PVC (IPVC) improved its resistance to electrical overloads and hot solder irons. However, IPVC does have several drawbacks:

1. Limited thermal stability
2. Corrosive outgassing
3. Incompatibility with some varnishes

New Material Needed

After several years of studying the irradiation effects on many materials, Haveg Industries concluded that there was not an off-the-shelf polymer which could fully utilize the potential of irradiation chemistry. To fill this void Haveg set out to develop its own polymeric system based upon the following considerations:

1. Cost
2. Thermal stability
3. Cold temperature properties
4. Flame resistance
5. Physical toughness
6. Electrical properties

The end result of this effort was EXAR -- Haveg's registered tradename for its cross-linked polymeric wire insulation system.

EXAR is oriented toward three market areas:

1. Motor lead wire
2. Commercial hook-up and appliance wire
3. Mil Spec hook-up wire

A brief explanation of each will reveal some of EXAR's properties.

Motor Lead Wire:

EXAR motor lead wire was designed primarily as a 600 volt, 125°C lead wire for industrial and appliance motors and coils. It is listed by Underwriters' Laboratories and recognized by Canadian Standards Association.

In Table I, comparing the properties of EXAR with chlorosulfonated polyethylene, both rated at 600 V, it can be noted that EXAR is superior with respect to:

1. Temperature rating: 125°C vs. 105°C
2. Insulation resistance: 80,000 megohms/MFT vs. 800 megohms/MFT
3. Dielectric constant: 2.4 vs. 8 to 10
4. Life cycle and accelerated aging

Electrical Properties:

Notice that while the dielectric strength of the two materials is about the same, the insulation resistance of EXAR® is far superior. Likewise the dielectric constant of EXAR is considerably lower. This can be expected since EXAR does not have any ionic chlorine attached to its polymer backbone.

High Temperature Capability:

It is the thermal stability, however, that separates EXAR from chlorosulfonated polyethylene.

The physical properties of EXAR are retained after heat aging at 158°C for 60 days. EXAR motor lead wire retains an average of 86% of its tensile strength and 74% of its elongation. Naturally under these conditions the chlorosulfonated polyethylene was too brittle to test.

Likewise under these aging conditions of 158°C for 60 days, EXAR has outstanding dielectric strength, whereas the electrical properties of chlorosulfonated polyethylene disintegrate. It is EXAR's high temperature performance which we feel gives the electrical design engineer additional capabilities without any increase in wire cost.

To give further evidence to the high temperature performance of EXAR, it passes the MIL-W-81044/9 life cycle test when run at 175°C for 168 hours. The life cycle test consists of placing a 24" length of wire with weights at each end over a mandrel in the oven. After aging for 168 hours the wire is removed from the oven and allowed to cool. The wire is then wrapped around a mandrel four times, twice in each direction. The wire is then soaked in a 5% salt solution for 5 hours. At the end of 5 hours the insulation must withstand 2,500 volts for 5 minutes.

Accelerated aging is a similar test to life cycle except the temperature is higher and the time shorter. EXAR motor wire passes the test at 250°C for six hours. This test is indicative of the overload protection that one gets with EXAR motor lead wire.

Life Expectancy:

A more definitive description of EXAR is given in the Arrhenius chart shown in Figure 1. Here by plotting the reciprocal of the absolute temperature vs. time it is possible to predict useful life at a particular temperature. The data on the chart was based upon heat aging results obtained at temperatures of 225°C, 200°C and 175°C using an elongation of 100% and a dielectric strength of 2000 volts as minimums. From our data you can see that at 175°C EXAR motor lead wire can last 552 hours. If we extrapolate this chart out to 125°C we can expect EXAR to have a life expectancy of more than 27,000 hours. Extrapolating the curve for chlorosulfonated polyethylene which was generated from manufacturer's literature, to obtain 27,000 hours of life, chlorosulfonated polyethylene could have a temperature rating of no more than 85°C.

Physical Properties:

EXAR will pass the penetration test when conducted at 125°C. The U.L. test calls for the blade to be "sharp." By U.L. definition this means something less than a 1 mil radius blade and not a 5 mil radius blade as is reported by some manufacturers. (When a 5 mil blade is used, a temperature differential of up to 45°C is found -- this is, samples tested with a 5 mil blade pass at 125°C, but when the "sharp" U.L. blade is used, these same samples will only pass at 80°C.) In addition EXAR has excellent abrasion resistance and flexibility down to -65°C.

Flammability and Corrosion Resistance:

EXAR motor lead wire passes the MIL-W-81044 - 60° flammability test and U.L. 758 horizontal flame test and when ignited, does not drip flamming particles. It is non-corrosive and does not give off any HCL fumes. It passes the Copper-Mirror Corrosion Test as described in ASTMD-2671 even with the temperature increased to 175°C. A copper mirror is placed above the test samples in a tightly corked test tube. The sealed tube is then placed in an oil bath at 175°C for 16 hours. If the insulation is corrosive, it will remove the copper from the mirror making the mirror transparent. If the area of transparency is 5% or greater the sample fails the test. Both PVC and chlorosulfonated polyethylene evolve corrosive fumes that remove all the copper, thereby failing the test.

Insulating Varnish Compatibility:

One of the most critical characteristics required for motor lead wire is compatibility with the varnish bake process. In most manufacturing processes portions of the lead wire are exposed to insulation varnish. During further processing this varnish is then baked on the lead wire. Subsequent flexing can cause some insulations to crack. Figure 2 shows a sample of cross-linked PVC that has cracked after a varnish bake process. EXAR is also compatible with magnet wire and has performed well in varnish bake processes up to 190°C. Figures 3 and 4 show examples of current EXAR applications.

Commercial Hook-Up and Appliance Wire:

EXAR has also been introduced as a commercial hook-up and appliance wire. In applications where the industry not only wants thinner walls, but also FR-1 flame resistance, EXAR now is U.L. listed for these applications in 10 mil, 16 mil and 1/32" wall thickness.

A comparison of the properties of EXAR and IPVC is given in Table 2. For the same wall thickness as IPVC, EXAR has an equivalent voltage rating and as would be expected, a higher tempera-

ture rating as much as 45°C for the 10 mil wall insulations. Though U.L. requirements for tensile strength are the same for EXAR® and IPVC, the vinyl insulations now being sold have a higher tensile strength but they are stiffer with less flexibility and hence more difficult to fabricate. At the same voltage and wall thickness U.L. listed EXAR gives the electrical design engineer higher temperature capability without any increase in cost.

The high temperature characteristics of EXAR are not lost when we go to thin walls. Some actual heat aged values for 10 mil wall EXAR are in Table 3. EXAR aged at 136°C for 90 days had no significant loss in either tensile or elongation. The samples aged at 175°C for two weeks had no loss in tensile and still had 170% elongation.

EXAR also has excellent solder iron resistance and is equivalent to IPVC and easily meets any requirement specified for IPVC. Ten mil wall EXAR can pass the 175°C life cycle test, which causes IPVC to embrittle and form a char on the conductor. The life cycle specifications for IPVC as advertised by one of the suppliers is only 135°C for 120 hours.

EXAR hook-up and appliance wire also meets the revised U.L. FR-1 vertical flame test and all known flammability requirements established for PVC.

Mil Spec Wire:

EXAR is also manufactured to the requirements of MIL-W-16878 types B and C. As with the case of other constructions, EXAR's outstanding thermal stability allows it to provide a considerable margin of safety over stipulated values.

Conclusion

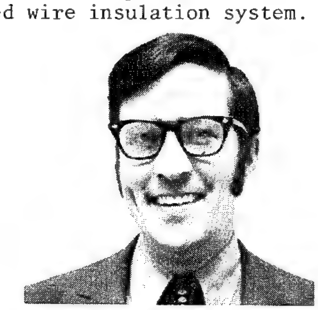
In short EXAR, Haveg's new cross-linked polymeric wire insulation, is an economical high temperature insulation system. It's outstanding properties are:

1. Low cost
2. Superior thermal stability
3. Excellent cold temperature properties
4. Flame resistance
5. Physical toughness
6. Excellent electrical properties

It has found broad acceptance in motor lead, appliance, hook-up and Mil spec applications and offers all industries more high temperature capabilities than are available from any equivalent material.

Nelson Hildreth
Supervisor, Research and Development
Haveg Industries, Inc.
Super Temp Wire Division
P. O. Box 7, Winooski, Vermont 05404

Mr. Hildreth graduated from the Polytechnic Institute of Brooklyn with a B.Ch.E. in 1960 and a M.S. in chemical engineering in 1962. He served in the U.S. Army from 1954 to 1957. After graduation Mr. Hildreth joined Hercules, Inc. at the Parlin Plastic Laboratory as a development engineer on polyolefins. He was then transferred to Haveg Industries, a Hercules subsidiary as a project manager in their commercial development department in Wilmington, Delaware. He became manager of process development for Haveg where he headed a research group on irradiation processing. In 1970 Mr. Hildreth was transferred to Haveg's Super Temp Wire Division in Winooski, Vermont to concentrate his efforts to develop EXAR®, Haveg's irradiated cross-linked wire insulation system.

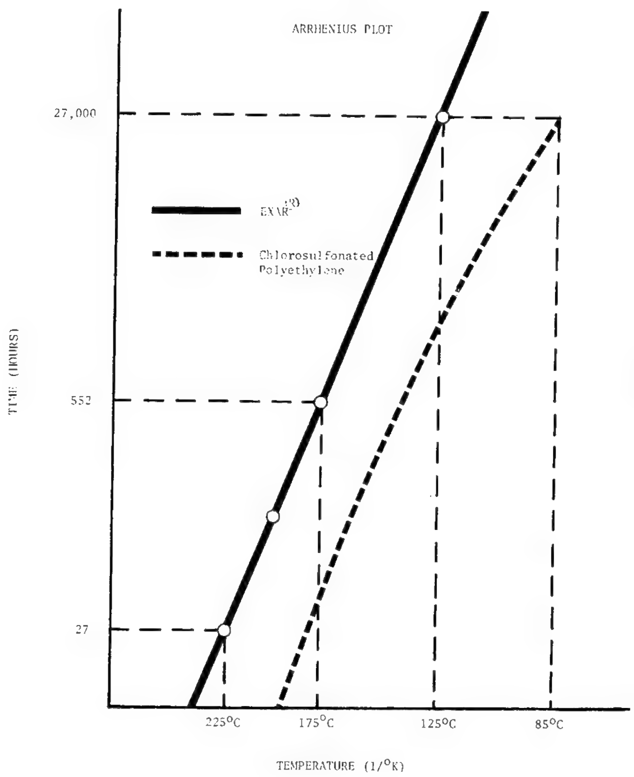


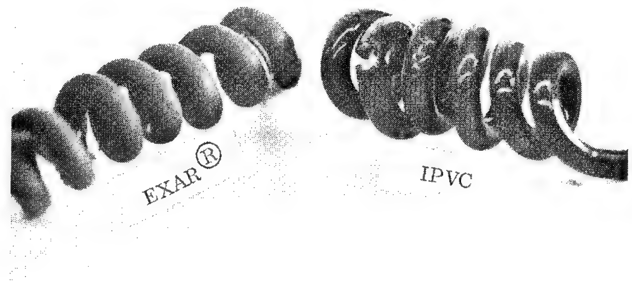
James F. Brooks
Market Development Supervisor
Haveg Industries, Inc.
Super Temp Wire Division
P. O. Box 7, Winooski, Vermont 05404

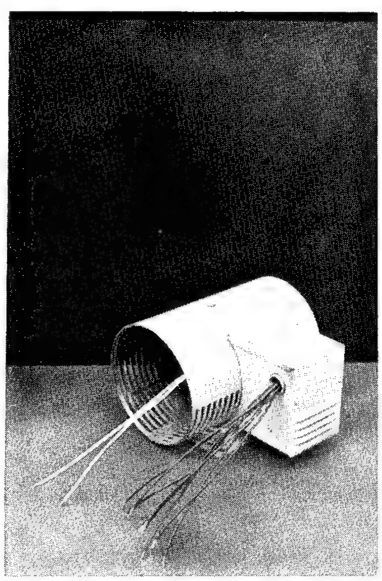
Mr. Brooks attended the University of Colorado where he majored in Business Administration. He has also attended and participated in numerous management training schools. He served in a United States Naval Air Reserve ASW Squadron from 1955 to 1963 with prime responsibilities in Ordnance.

He has been employed by Haveg Industries, Inc., Super Temp Wire Division, a subsidiary of Hercules, Inc., since 1965. Until August of 1971, he was Midwest Division Sales Manager with prime responsibility for Sales and Administration of Super Temp Wire Division products in that area. Effective September 1, 1971 he was appointed Market Development Supervisor at the Burlington Operation with the responsibility for the development and marketing of new products.

FIGURE I


ARRHENIUS PLOT
27,000
552
27
TIME (HOURS)
EXAR®
Chlorosulfonated Polyethylene
225°C
175°C
125°C
85°C
TEMPERATURE (1/°K)


EXAR®
IPVC



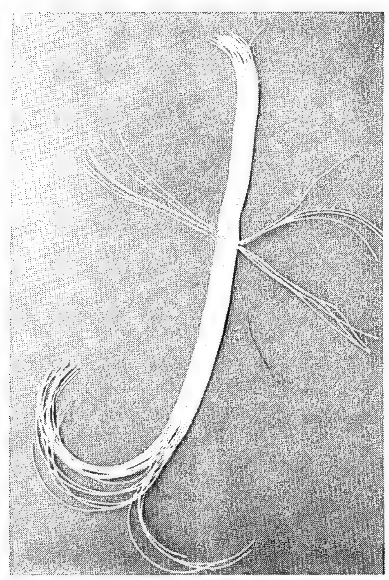


TABLE I

MOTOR LEAD WIRE

EXAR® VS. CHLOROSULFONATED POLYETHYLENE

PROPERTY	METHOD	REQUIRED	CHLOROSULFONATED POLYETHYLENE	EXAR
Voltage Rating	N/A	N/A	600 VRMS	600 VRMS
Temperature Rating	N/A	N/A	105°C	125°C
Dielectric Strength	Mil-W-22759	–	500 Volts/Mil	600 Volts/Mil
Insulation Resistance	ASTM D257	–	800 Megohms/MFT	80,000 Megohms/MFT
Dielectric Constant	ASTM D150	–	8-10 @ 1 MHZ	2.5 @ 1 MHZ
Dielectric Strength Control	UL Sub. 758, Method I, Para. 41 11/27/63	2000 Volts	Passes	Passes
Heat Aged 60 Days @ 158°C		2000 Volts	Fails	Passes
Heat Shock	UL Sub. 62 Para. 68	180°C	–	Passes
Deformation 180°C with 500 Gram	UL Sub. 62 Para. 70	50% Max.	–	Passes
Tensile Strength Control	UL Sub. 62 Para. 310	1500 PSI	Passes	Passes
Heat Aged 60 Days @ 158°C		70% Retention	Fails	Passes
Elongation Control	UL Sub. 62 Para. 310	150%	Passes	Passes
Heat Aged 60 Days @ 158°C		50% Retention	Fails	Passes
Life Cycle	Mil-W-81044/9	175°C for 168 Hrs. 2.5 KV for 5 Mins.	Fails	Passes
Accelerated Aging	Mil-W-81044/9	250°C for 6 Hrs. 2.5 KV for 5 Mins.	Fails	Passes
Penetration	UL 758 125°C 350° gram with .0005" blade	–	–	Passes
Abrasion	Mil-T-5438 4/0 Grit	25"	–	Passes
Cold Bend	UL Sub. 758 Para. 34	-65°C	–	Passes
Flame Test	81044	No Flaming Drip	–	Passes
	UL 758 Para. 39	No Flaming Drip	–	Passes
Corrosion	Copper Mirror Test ASTM 2671 at 175°C	5% Transparency Max.	Fails	Passes

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TABLE II

EXAR® HOOK-UP AND APPLIANCE WIRE VS. IRRADIATED CROSS-LINKED PVC

		10 MIL WALL		1/64" WALL		1/32" WALL	
		IPVC	EXAR	IPVC	EXAR	IPVC	EXAR
PROPERTY	METHOD	U.L. 1429	U.L. 3265	U.L. 1430	U.L. 3266	U.L. 1431	U.L. 3271
Voltage Rating	N/A	Not Specified	150 VRMS	300 VRMS	300 VRMS	600 VRMS	600 VRMS
Peak	N/A	300 VRMS	300 VRMS	600 VRMS	600 VRMS	2500 VRMS	2500 VRMS
Temperature Rating	N/A	80°C	125°C	105°C	125°C	105°C	125°C
Tensile Strength As Received	U.L. STD 62 Class 12	1500 PSI Min.	1500 PSI Min.	1500 PSI Min.	1500 PSI Min.	1500 PSI Min.	1500 PSI Min.
Tensile Strength After Aging 7 Days At *°C; Per Cent Retention	U.L. STD 62 Class 12	*113°C 70% Min.	*158°C 70% Min.	*136°C 70% Min.	*158°C 70% Min.	*136°C 70% Min.	*158°C 70% Min.
Elongation As Received	U.L. STD 62 Class 12	100% Min.	150% Min.	100% Min.	150% Min.	100% Min.	150% Min.
Elongation After Aging 7 Days At *°C; Per Cent Retention	U.L. STD 62 Class 12	*113°C 65% Min.	*158°C 65% Min.	*136°C 65% Min.	*158°C 65% Min.	*136°C 65% Min.	*158°C 65% Min.
Solder Iron Resistance 45° Angle, 1.5 Lbs. 660°F; Seconds To Failure	Haveg	300 Sec.	300 Sec.	Not Tested	Not Tested	Not Tested	Not Tested
Heat Shock Mandrel Wrapped One Hour At *°C No Cracking	U.L. Sub. 758 Sec. G, Pg. 37	1/16" Mandrel 121°C	1/16" Mandrel 158°C	1/16" Mandrel 136°C	1/16" Mandrel 158°C	3/32" Mandrel 136°C	1/16" Mandrel 158°C
Life Cycle 20 AWG, 3/4" Mandrel; .38 Lbs., 2.5 KV/5 Mins.	Mil-W-81044/13	120 Hrs. @ 135°C	168 Hrs. @ 175°C	Not Tested	168 Hrs. @ 175°C	Not Tested	168 Hrs. @ 175°C
Flammability Vertical, FR-1	U.L. Sub. 758 Sec. G, Pg. 95	Passes	Passes	Passes	Passes	Passes	Passes
Corrosion Copper Mirror Test	ASTM D-2671 Tested at 175°C	Fails	Passes	Not Tested	Passes	Not Tested	Passes
Deformation 50% Max. Change In Wall Thickness After 1 Hour At *°C	U.L. Sub. 758 Sec. G, Pg. 38	*121°C 250 Grms.	*158°C 250 Grms.	*121°C 250 Grms.	*158°C 250 Grms.	*121°C 250 Grms.	*180°C 250 Grms.

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TABLE III

EXAR®

HEAT AGING RESULTS

10 MIL WALL (UL - 3265)

	TENSILE STRENGTH (PSI) (% RETENTION)	ELONGATION PERCENT (% RETENTION)
30 Days at 136°C	2413 (115%)	410 (119%)
60 Days at 136°C	2526 (120%)	466 (133%)
90 Days at 136°C	1923 (92%)	400 (116%)
7 Days at 175°C	2353 (95%)	230 (85%)
14 Days at 175°C	2583 (104%)	170 (65%)

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HIGH TEMPERATURE ELECTRICAL WIRE INSULATION DEVELOPMENT

William L. Lehn

Materials Technology Department
Components and Materials Laboratories
Hughes Aircraft Co.
Culver City, California

U. S. Air Force Materials Laboratory
Elastomers and Coatings Branch
Wright Patterson A. F. B.
Ohio

Abstract

New high temperature polymeric wire insulations for multistrand electrical connector wire have been developed. Excellent low and high temperature properties were obtained. The maximum temperature for continuous indefinite service exceeds that of the current MIL-W-81381 polyimide - Teflon FEP insulation wire by 150°F. The insulation appears to offer 1000 hours service at 600°F and short term (several hours service) at 700°F. It passes cold bend, life cycle, and electrical resistance tests and has cut-through resistance at 700°F. Resistance to radiation is outstanding. The insulation is suitable for mass production on commercial wire wrapping machines and can be prepared in the same form (single, double, or triple wrapped), as the currently available MIL-W-81381 polyimide wire. A proposed Military Specification Sheet covering this insulation material has been drafted and submitted to the custodian for MIL-W-81381 for further government and industry consideration and coordination. The insulation was developed as the result of intensive investigation of a broad variety of new high temperature polymeric materials.

Introduction

The operation of aircraft at speeds in excess of Mach 3 has resulted in markedly increased temperatures to which aircraft hook-up wires are exposed. Temperatures of around 550°F are commonly experienced on contemporary aircraft, while temperatures of 800°F and possibly higher will be experienced in future hypersonic aircraft. These temperatures are considerably in excess of those that existing aircraft hook-up wires can safely withstand under sustained conditions.

A common high temperature hook-up wire currently specified for military aircraft has a thin, tough insulation. This insulation is constructed from tapes that are composites of a fluorocarbon copolymer and a polyimide. The wire has a continuous service temperature rating of 392°F, and above this the softening point of the fluorocarbon sealant is exceeded. As a result, the fluorocarbon loses its sealant properties, and general reduction in mechanical properties is observed. Consequently, one way to improve the thermal threshold of hook-up wire is to replace the fluorocarbon sealant by a sealant which has a service temperature as high as that of the polyimide substrate.

Many high temperature polymers that warranted evaluation as sealants and substrates for electrical insulation have been under development in laboratories throughout the world. Polyimides, silicone carboranes, polyphenylenes, perfluoroalkylenetriazines, polypyrrolones, polybenzimidazobenzophenanthroline (BBB), and BBL resins, polybenzothiazole, poly(terphenylene oxide), and polyimidazoquinazoline were selected as primary candidate materials because of the high probability that they would meet the high temperature insulation requirements. Furthermore, several of these polymers were available in research quantities and consequently their evaluation was feasible within the scope of this program. Other rarer prospective polymers also exist and warrant screening in subsequent studies.

Discussion

The research described herein was performed at the Hughes Aircraft Company under U. S. Air Force Materials Laboratory Contract. The objective of this program was to develop high temperature wire insulation that could meet the requirements of Military Specification MIL-W-81381 but which would have the capability of withstanding continuous temperatures up to 800°F. Several new extreme temperature insulations were developed, which showed promise of utility at temperatures as high as 700°F for moderate periods of time.

Insulation requirements which were goals of the program included the ability to be mechanically stripped so that the wire would be useful as a hook-up wire, resistance to blocking when stored at temperatures of -65° to over 165°, a dielectric breakdown strength over 2500 volts AC, an insulation resistance above 1000 megohms per 1000 feet of wire, low temperature flexibility down to -65°F and thermal stability to 800°F. Other requirements were good high temperature

humidity resistance, resistance to breakdown or peeling after a 28-day exposure to 180°F and 95 percent relative humidity and good cut-through resistance when an 800 gram load was applied to the wire for 24 hours. In addition the insulation was to have a good temperature profile and show good adhesion without failure at temperatures up to 800°F.

High temperature polymers have been under development by the U.S. Air Force Materials Laboratory, NASA, and many other laboratories. Although many of these new polymers have temperature capabilities above 600°F and several of them as high as 800°F, the best potential candidate insulations tend to lack processability. That is, they are neither fusible nor soluble in solvents which would allow them to be used in thermosetting polymer varnishes suitable for coating processes. Consequently, in spite of their extremely high temperature capability many of these materials could not be processed into wire insulation.

One way in which they might be utilized was as sealants or adhesives for commercially available polyimide film. The best commercial high temperature polymeric wire insulations available today are made from polyimide film coated with Teflon FEP. The limiting component in this type of construction is the fluorocarbon sealant since it is not capable of withstanding temperatures as high as those which the polyimide substrate itself can withstand. Consequently, if a superior sealant material could be found to replace the fluorocarbon, the composite insulation would have upgraded thermal capability.

One of the new high temperature polymers which was evaluated in this capacity was the polypyrrolone whose structure is shown in Figure 1. This polymer had previously been studied in Hughes Aircraft Company and other laboratories, although not as insulation, and had been reported to be a highly intractable, infusible, insoluble material. Consequently, in its original form it also was not satisfactory for insulation production. After several years of research at Hughes a process was developed by which polypyrrolones could be made in a fusible, soluble from which subsequently could be cured into an intractable state, but which could be processed into insulation while it was in the soluble, fusible state. The processable form of the polymer was designed HR-100. Its unique properties were a direct consequence

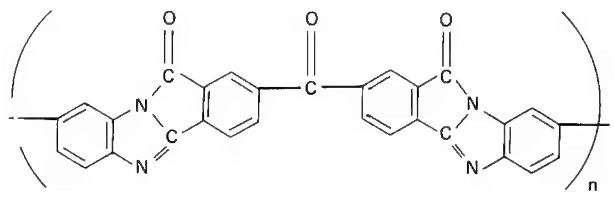

Figure 1. HR-100

of the specific intermediates used in its synthesis and the method of preparation.

In addition to evaluating new high temperature polymers as potential sealants for polyimide film, several were also evaluated as overcoats for the polypyrrolone/polyimides insulation described herein. Two of the materials were elastomeric and could conceivably have functioned as either overwraps or as sealants. These were perfluoroalkylenetriazine, and silicone carborane. Poly-(terphenylene oxide) was also evaluated as an overcoating as well as a primary coating but was found to be excessively brittle. Furthermore, none of these three materials showed sufficiently good adhesion to polyimide to be useful as either a sealant or as an overcoat.

The substrate insulation which was used in this work was Kapton polyimide, a product of Du Pont. Its structure is shown in Figure 2. In utilizing it as a substrate, solutions of the few experimental polymers which were soluble were used to coat the Kapton polyimide tapes, and the tapes were subsequently wrapped onto 19/32 20-gauge silver-plated multifilament wire.

The dielectric properties of the Hughes HR-100 polypyrrolone are:

dielectric constant = 3.2 at 1 KHz

dissipation factor = 1.2 percent at 1 KHz

insulation resistance = 5×10^{12} ohms at 500 volts DC

volume resistivity = 2.8×10^{14} ohm-centimeters.

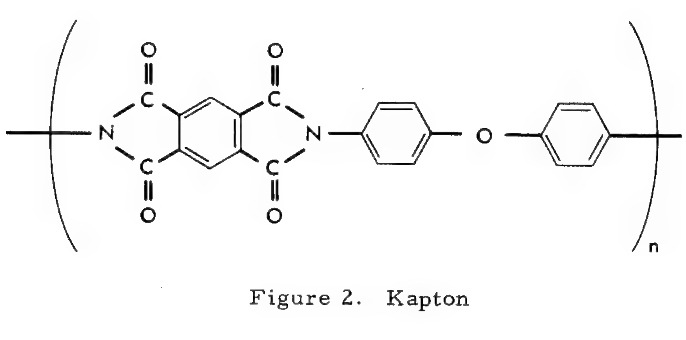

Figure 2. Kapton

The insulation resistance of HR-100/Kapton wrapped multifilament wire as a function of temperature is shown in Figure 3. Data on four wires are presented. Wire II had the double-wrapped HR-100/Kapton insulation and both the first and second layers had a 50 percent overlap. However, the second layer was wrapped in the opposite direction to that of the first. This basic wire was used to make three other insulated wires shown on the graph as IIA, IIB, and IIC. Wire IIA had a single layer of 2-mil Teflon TFE as an overwrap. Wire IIB had two layers of Teflon TFE overwrap, and Wire IIC had one layer of Teflon FEP copolymer as an overwrap. In this figure it is evident that the double-wrapped HR-100/Kapton insulated wire had an insulation resistance between 10^{13} and 10^{14} ohms; at 600°F this had fallen to 10^7 ohms with the drop-off being in a relatively uniform. All three of the fluorocarbon-overcoated wires showed superior retention of properties at 600°F with the best of the three (IIB and IIC) having an insulation resistance at 600°F of almost 10^{12} ohms. It should be noted, however, that under prolonged exposure at 600°F and above the fluorocarbon overcoat tended to embrittle and crack. Nevertheless the overcoat did provide improved long term survivability.

When the HR-100/Kapton insulated wire was exposed to the 185°F 95 percent relative humidity environment for 28 days its insulation resistance at ambient temperature dropped about 3-4 orders of magnitude below its normal dry insulation resistance, but upon drying at 300°F for 1 hour, its insulation resistance was restored essentially to its value prior to the exposure. Furthermore, at temperatures of 300°F to 600°F, the insulation resistance is within one order of magnitude of that of the unexposed wire. The fluorocarbon overcoated HR100/Kapton insulations easily withstood the humidity tests and their dielectric properties normalized completely upon drying.

Figure 4 illustrates the change in insulation resistance of several HR-100/Kapton insulated wires as a function of thermal aging in air at 550°F. Values shown were measured at ambient temperature. Periodically during the aging period, wires were removed from the oven, measurements were made, and they were again placed into the oven, giving a many cycled exposure. Figure 4 presents data on 4 different wire

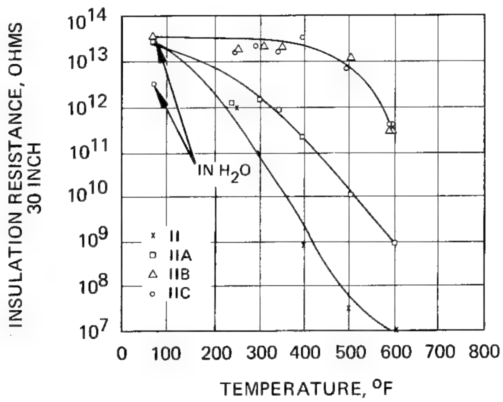

Figure 3. Insulation Resistance of Teflon Overcoated HR-100/Kapton Insulated Wires as a Function of Temperature

constructions. Insulation resistance of the double-wrapped HR-100/Kapton insulation remained at 10^{13} ohms throughout the test period of over 2400 hours, and the wire finally shorted out at 2456 hours. The other three types of insulation were also double-wrapped HR-100/Kapton, but they were overcoated with fluorocarbon polymers. These latter three all had insulation resistances which remained over 10^{14} ohms throughout the 2456 hour test. Single-wrapped HR-100/Kapton insulated wires prepared from 2 mil Kapton tape were also aged at 600°F. In Figure 5 the results of these insulation resistance measurements are shown. Here a continuous, but relatively uniform drop in the HR-100/Kapton insulation resistance with time can be noted and after 500 hours the resistance had dropped from 10^{14} ohms to 10^7 ohms. However, the best of the fluorocarbon-overwrapped wires showed no evidence of deterioration prior to 500 hours. Here also, measurements were made at ambient temperature by removing the wires from the ovens.

Analogous tests were made on the double-wrapped HR-100/Kapton insulated wires by aging them at 600°F in air, and these test results are shown in Figure 6. Here the ambient temperature insulation resistance of the double-wrapped HR-100/Kapton insulated wire fell from

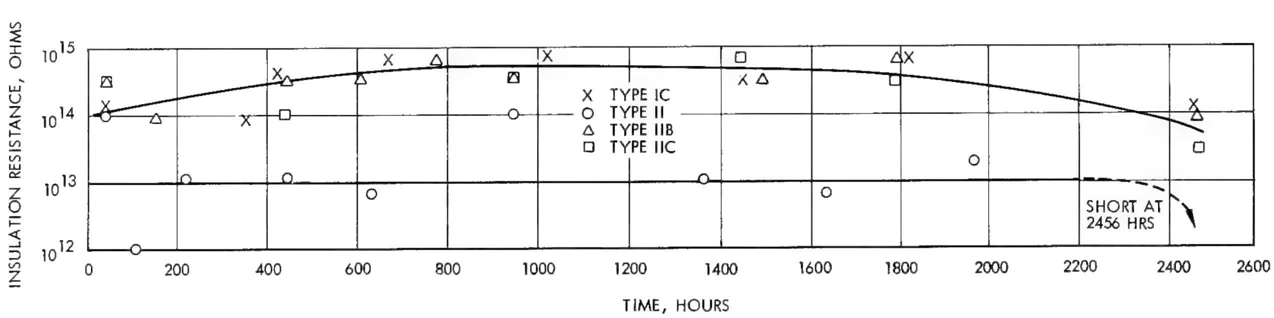

Figure 4. Insulation Resistance as a Function of Thermal Aging in Air at 550°F — HR-100/Kapton

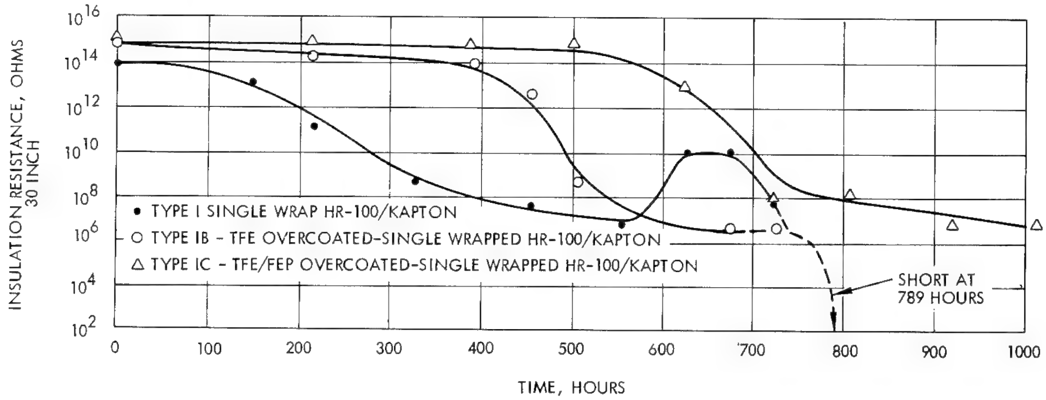

Figure 5. Insulation Resistance as a Function of Thermal Aging in Air at 600°F

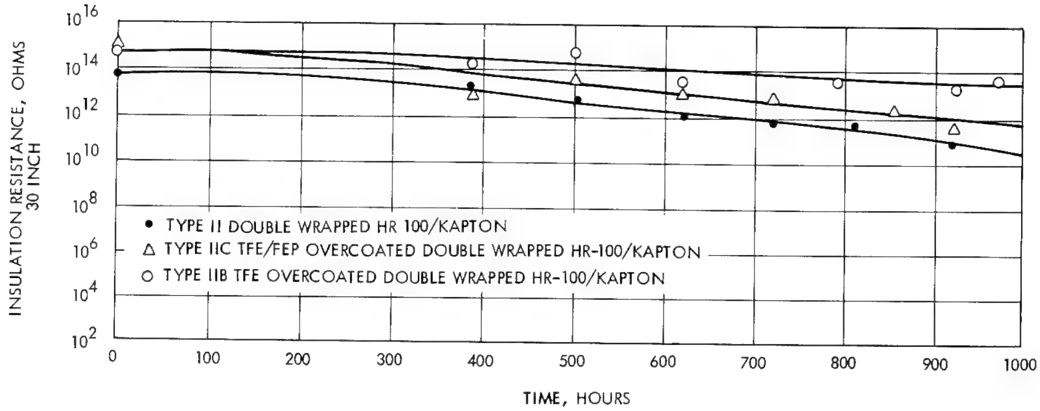

Figure 6. Insulation Resistance as a Function of Thermal Aging in Air at 600°F

10^{14} to 10^{11} ohms in 1000 hours. In comparison the insulation resistance of the double-wrapped HR-100/Kapton wire overcoated with Teflon FEP had fallen from 10^{15} to 10^{13} ohms over the same 1000-hour period. None of these wires had failed at the completion of the test period.

Another type of polypyrrolone which was examined, and which also was developed at Hughes, is HR-300; its chemical structure is shown in Figure 7. This material was first synthesized rather late in the program, and consequently test data on it are much more limited. Nevertheless, efforts to make the polymer in a processable form were highly successful and wire insulation was also successfully prepared. This material appeared to be even better than the HR-100 when used as the Kapton sealant.

The HR-300 polymer differs from HR-100 in that it has an extra carbonyl group at the extreme right of the polymeric unit illustrated in Figure 7. In Figure 8 a comparison of the HR-100/Kapton insulated wires and the HR-300/Kapton insulated wires is made. None of these wires had the fluorocarbon overcoats. For each type there was a double-wrapped and a triple-wrapped version. Very little difference was noted between the double-wrapped and triple-wrapped versions of either of the HR-100/Kapton or the HR-300/Kapton composite insulations; however, as will be noted later, the triple-wrapped wires showed superior performance in 700°F air aging tests and the HR-300 combination did appear to be better than the HR-100 combination. In this case, the insulation resistance of the HR-300/Kapton insulated wires fell from about 10^{13} ohms at 300°F down to 10^8 ohms at 600°F.

Comparisons of the HR-100/Kapton and HR-300/Kapton insulated wires were also made in air at 700°F. Results of these tests are shown in Figure 9. Here both double-wrapped wires survived approximately 100 to 117 hours before shorting out, and the HR-300/Kapton wire was

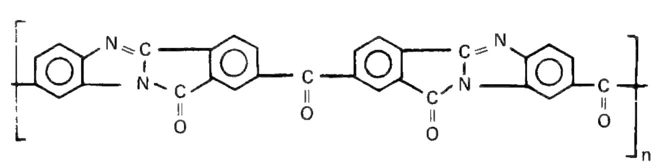

Figure 7. HR-300

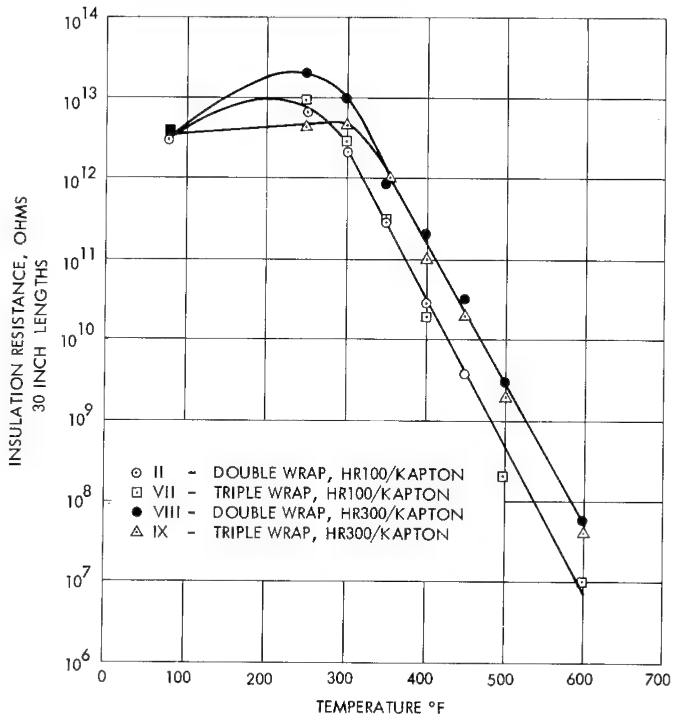

Figure 8. Insulation Resistance as a Function of Temperature. Wires II, VII, VIII, and IX

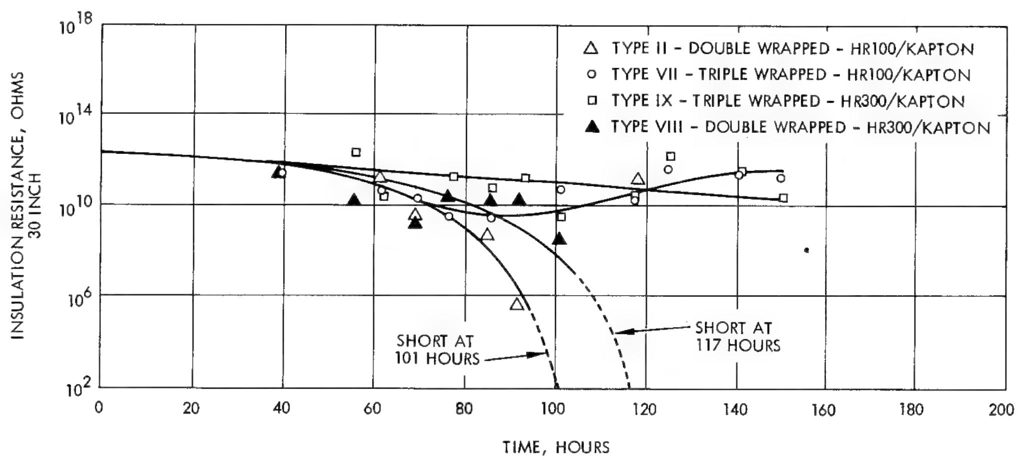

Figure 9. Insulation Resistance as a Function of Thermal Aging in Air at 700°F — HR-100/Kapton and HR-300/Kapton

slightly better than the HR-100/Kapton, having survived a total of 117 hours. In contrast the triple-wrapped wires had not failed up to 150 hours, at which time the tests were terminated. Ambient temperature insulation resistances in both cases were over 10^{10} ohms after the 150-hour, 700°F exposure.

Another evaluation test which was performed on the HR-100/Kapton wires was insulation cut-through. Cut-through tests were not performed on the fluorocarbon overcoated HR-100/Kapton insulated wires once it was demonstrated that the HR-100/Kapton primary insulation easily passed this test. To perform the tests a load of 8000 grams was applied at 75°F and a 3000 gram load at 500°F, 600°F, and 700°F. In no case was failure noted for any of the HR-100/Kapton insulated wires.

Another polymer which was successfully utilized to produce a high temperature insulation was P13N, a polyimide from Ciga-Geigy Corporation. The structure of this polymer is shown in Figure 10.

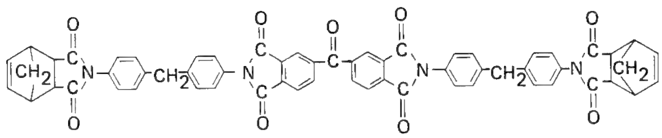

Figure 10. P13N

Insulation resistance measurements on P13N/Kapton insulated wires as a function of temperature are shown in Figure 11. Here also, as in the case of HR-100/Kapton type insulations, both single-wrapped and double-wrapped wires were prepared. As anticipated, the double-wrapped wire was superior to the single-wrapped wire. The insulation resistance of the double-wrapped wire at 600°F was 10^8 ohms, having fallen from near 10^{14} ohms at ambient temperature. Air aging tests were also carried out on the P13N/Kapton insulated wires at 550°F and 600°F. The 550°F test results on three types of insulation are shown in Figure 11. Type V is double-wrapped P13N/Kapton, whereas type IVA and IVB were single-wrapped P13N/Kapton with overwraps of Teflon TFE fluorocarbon. It will be noted that the double-wrapped wire had an ambient temperature insulation resistance originally of approximately 10^{14} ohms, and after 1000 hours at 550°F this had fallen to around 10^{10} ohms. In contrast the insulation resistance of the fluorocarbon-overwrapped P13N/Kapton wires remained above 10^{14} ohms for the complete test duration of 1700 hours.

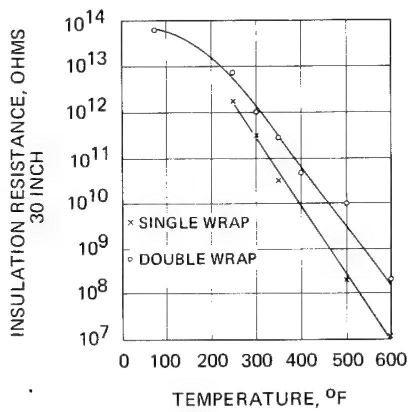

Figure 11. Insulation Resistance of P13N/Kapton Insulated Wire as a Function of Temperature

Corresponding tests were also carried out at 600°F. Figure 13 shows the results from four wires of this general type. These were the single-wrapped P13N/Kapton, the double-wrapped P13N/Kapton and two fluorocarbon overcoated versions of the single-wrapped wire. It will be seen from this graph that the ambient temperature insulation resistance of the double-wrapped P13N/Kapton insulated wire, even without a fluorocarbon overcoating, remained above 10^{10} ohms, even after 1000 hours at 600°F. Insulation resistance measurements were made at ambient temperature although the wires were aged at 600°F. In making the measurements wires were removed from the oven, cooled to ambient temperature, tested, and replaced into the oven.

P13N/Kapton insulation was unusual in one respect, in comparison to HR-100/Kapton insulation, in that the single-wrapped wire performed better than the same wire overcoated with fluorocarbon polymer. With this insulation, degradation of the P13N sealant might be catalyzed by HF liberated from the fluorocarbons during the 600°F exposure

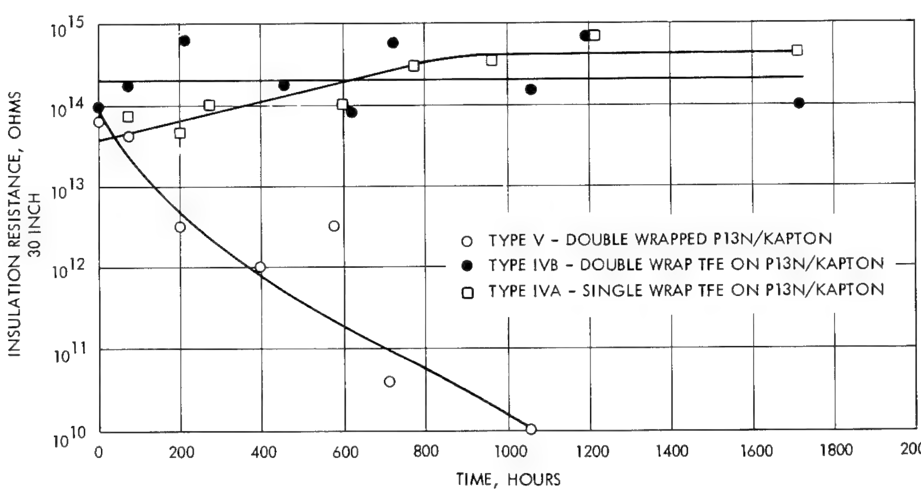

Figure 12. Insulation Resistance of Various P13N/Kapton Wires as a Function of Thermal Aging at 550°F

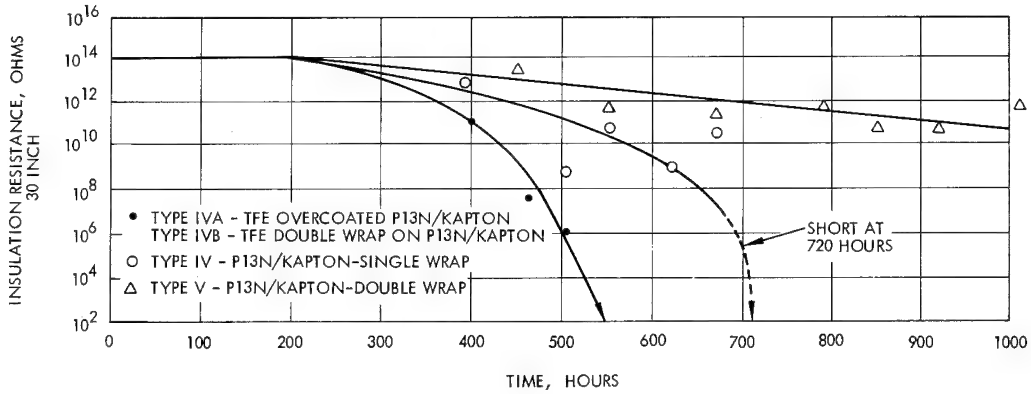

Figure 13. Insulation Resistance as a Function of Thermal Aging in Air at 600°F — P13N/Kapton

period and this may account for the unusual results.

Dielectric breakdown measurements were made on all of the HR-100/Kapton insulated wires and the P13N/Kapton insulated wires. Initial tests were performed by applying an A. C. potential between the anionic wetted water in which the wires were submerged and the wire conductors. The voltage was increased from zero, at a rate not exceeding 500 volts per second, to a potential of 2500 volts, and after 1 minute it was decreased to zero at a rate of 500 volts per second. Upon completion of this test total breakdown was run. The double-wrapped HR-100/Kapton insulated wire was found to have a breakdown voltage of 16.5 KV, or 3.8 KV per mil. The fluorocarbon-overcoated HR-100/Kapton insulation survived 25 KV or 2.4 KV per mil. The single-wrapped P13N/Kapton wire (type IV) withstood 16 KV or 10.8 KV per mil.

Life cycle bend tests were also performed in accordance with Military Specification MIL-W-81381. For these tests two weights, 3/4 pound each, were attached to the ends of the wire which was hung over a 1/2-inch diameter mandrel in air at 600°F for 24 hours. The wires were then removed from tension and straightened. Three single-wrapped HR-100/Kapton insulated wires and the double-wrapped HR-100/Kapton wire were tested. Both of the fluorocarbon-overwrapped HR-100/Kapton wires and the double-wrapped wire passed this test.

Subsequently wires were wound under tension around the 1/2-inch diameter mandrel for their entire length, then unwound and rewound in the opposite direction. This test was performed only on the type I, IA and IB wires and of these only IA and IB retained their integrity as evidenced by a subsequent insulation resistance test in 5 percent aqueous sodium chloride solution. Similar tests using a 1/4-inch diameter mandrel showed that none of the wires could withstand this amount of bending.

Cold bend tests were conducted at -85°F after the wires had been exposed to this temperature for 4 hours. Tests were performed by wrapping the wires around a 1/4-inch diameter mandrel revolving at the rate of 2 rpm and subsequently measuring their insulation resistance and comparing the results to those made prior to the test.

Although the single-wrapped HR-100/2 mil Kapton wire (type I) failed this test, the double-wrapped HR-100/1 mil Kapton wire (type II) passed. Fluorocarbon overcoated versions of these wires (IA, IB, IC, IIA, IIB, and IIC) and the P13N/Kapton wire (type IV) were also tested and results of the tests are tabulated below.

Wire Type	Insulation Resistance, Ohms Before	After	Comments
I	3×10^{13}	$\simeq 10^{8}$	Wrinkled but no evident cracks
IA	4×10^{13}	5×10^{12}	Wrinkled but no evident cracks
IB	8×10^{13}	4×10^{12}	Wrinkled with one crack evident
IC	2×10^{14}	2×10^{13}	
II	5×10^{13}	1×10^{13}	Wrinkled but no evident cracks
IIA	4×10^{13}	1×10^{10}	Badly cracked
IIB	2×10^{14}	1×10^{13}	
IIC	2×10^{14}	2×10^{13}	
IV	6×10^{13}	5×10^{12}	

Summary

Several newly developed wire insulations have shown excellent property retention when aged in air at temperatures of 550°F, 600°F and 700°F. The 700°F tests indicated that the best

insulations could withstand time periods of 30-40 hours at that temperature without failure. Furthermore, they could be rated as suitable for continuous exposure at about 500°F.

Aside from the variation of the fluorocarbon overcoats three new basic types of insulated wires were successfully produced. They included wires wrapped with HR-100 bonded polyimide, HR-300 bonded polyimide, and P13N bonded polyimide. All three of the new polymers were used as sealants for Kapton in place of the conventionally used perfluorinated ethylene propylene sealant.

Although the HR-100 and HR-300 type polypyrrolones were developed at Hughes, they have not been marketed and it is not the intention of this company to do so. However, a pilot plant quantity of the HR-100 type polypyrrolone has been prepared in accordance with Hughes specifications, and a scaled-up manufacturing process has thus been demonstrated to be feasible. In addition, two wire manufacturers have cooperated with Hughes in wrapping wire, and conventional wrapping equipment has been shown to be adequate for production. In contrast the P13N type polyimide is commercially available from Ciba-Geigy Corporation.

A modified MIL-W-81381 specification on double-wrapped HR-100/Kapton insulation has been prepared for the Air Force and currently is in the process of being approved.

Dr. Norman Bilow

Dr. Bilow received his B. S. degree in Chemistry in 1949 from Roosevelt University, Chicago, Illinois, and his M. S. and Ph. D. in 1952 and 1956, respectively, from the University of Chicago. He is the author of 11 scientific papers, inventor on 15 patents, and author of numerous corporation and U. S. Government Contract Research Reports dealing with high temperature plastics, electrical insulation, ablative materials, polyphenylenes, and various other subjects. After working as a research chemist for Dow Chemical Company from 1949-1952 he joined the Hughes Aircraft Company where he has remained for the past 13 years. During much of this time he was Head of the polymer, physical, and analytical chemistry section and is currently the Senior Scientist of the Materials Technology Department. He is a former member of the New York Academy of Sciences, a current Fellow of the American Institute of Chemists, and a member of Sigma Xi, Scientific Research Society of America and the American Chemical Society. His biography has appeared in the Dictionary of International Biography (1970-), Who's Who in the West (1969-), American Men of Science (1968-) and Two Thousand Men of Achievement (1971). He was the recipient of the Industrial Research Magazine "IR-100" award in 1970.

Dr. William L. Lehn

Dr. Lehn received his B. S. degree in Chemistry from the University of Illinois in 1954 and his Ph. D. from the University of Rochester in 1958. After completing his formal education he joined E. I. duPont de Nemours where he worked as a research chemist from 1958-1960. Subsequently he joined the Air Force Materials Laboratory, where he has remained for the past 12 years. His first assignment there was with the Polymer Branch but he has since become the Technical Area Manager of the Elastomers and Coatings Branch. He is the author of 17 scientific publications, 11 Air Force Technical reports and inventor on 2 patents. His work has dealt with organic syntheses, organo metallic compounds, inorganic polymers, and radiation effects on materials. Dr. Lehn's biography appears in Who's Who in the Midwest and American Men of Science. He is also a member of the American Chemical Society and the Research Society of America as well as a Fellow of the National Institute of Health.

NEW HIGH TEMPERATURE, FLAME-RESISTANT, THERMOPLASTIC PVC WIRE INSULATION

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Abstract

PVC wire insulations designed to meet tentative Underwriters' Laboratories' 125°C specifications have been developed through the judicious balance of component variables. These include certain high molecular weight PVC resins, low volatility plasticizers and lead stabilizer systems. A new, unique lead stabilizer-filler additive (LECTRO®125) is introduced and experimental data presented demonstrating its effectiveness in forming thermoplastic high temperature PVC insulations. The resultant products exhibit an optimum balance of electrical, thermal, flame resistance and mechanical properties, including resistance to penetration at the rated temperature.

Introduction

For many years the electrical industry has utilized PVC based compounds as insulation for low voltage wire and cable constructions. Continuing improvements in PVC stabilization and plasticizer technology have resulted in the development of quality PVC insulation capable of receiving up to a 105°C Underwriters' Laboratories (UL) rating.

In recent years, however, reports from the wire and cable industry have shown a growing demand for high quality, low cost wire insulations capable of meeting performance ratings in the 105° to 150°C range. Newer, more stringent governmental and industrial specifications have placed a further burden on the wire and cable manufacturer to produce insulations with improved flame resistance, as well as resistance to physical degradation and thermal deformation. This demand has only been partially satisfied through the use of the fluorocarbons, silicone rubbers, cross-linked PVC or polyethylenes. Each of these materials has a deficiency in one or more key areas, i.e., flame resistance, thermal stability and/or cost.

Conventional thermoplastic PVC compositions, although possessing good flame resistance and low cost advantages, are also seen to be unsuitable for use in higher than 105°C applications, primarily because of poor resistance to deformation and flow at these elevated temperatures.

N L Industries, for many years a leading supplier of lead stabilizer additives for the PVC electrical insulation field, initiated an extensive research program designed to develop a low cost, flexible, flame-resistant PVC insulation compound capable of specifically meeting the requirements of a UL rated 125°C wire as outlined in UL Subject 758 titled "Tentative Outline of the Investigation of Thermoplastic Insulated Appliance Hook-Up Wire", November 27, 1963.

Although there are numerous industrial and governmental specifications available, it was felt that this particular UL specification best typified the overall requirements demanded by the wire and cable industry for evaluating wire constructions rated in the 105°-150°C range.

Our investigation, and the resulting data, will be discussed in two phases: 1) Development studies on laboratory prepared compression molded plaques; 2) Data developed on extruded wire insulation.

The first will serve to establish the variations in component type and level necessary to meet two key UL Subject 758 requirements, namely, Retention of Elongation and Tensile Strength after 7 Day - 158°C oven aging and Penetration Resistance at 125°C. All studies were performed exclusively on laboratory prepared 20 mil compression molded specimens. The second phase will demonstrate that quality finished wire construction can be extruded, capable of meeting the series of tests outlined in UL Subject 758.

PVC Resin-Plasticizer-Filler Requirements

Initial investigations sought to develop a 125°C rated electrical insulation through modification of the PVC and plasticizer components normally employed to prepare quality 105°C rated materials. A formulation consisting of PVC resin (100), plasticizer (50), electrical grade lead

stabilizer, i.e., LECTRO 60®XL, DYTHAL®XL, or TRIBASE*XL, (10) was used as a base formulation.

The data in Table I show the effects of substituting an ultra-high molecular weight PVC resin (ASTM D 1243-66 Inherent Viscosity >1.3) for an electrical grade high molecular weight (Inherent Viscosity 1.1 - 1.19) PVC used in 105°C rated insulation. In all cases, the ultra-high PVC was seen to significantly improve the Retention of Elongation properties after both 7 Day - 158°C and 60 Day - 136°C oven aging of 20 mil compression molded specimens.

Table II shows the aging characteristics of three plasticizer systems often employed in 105°C rated insulation, namely, Normal Trialkyl Trimellitate (Hooker Chemical NTM), Dipentaerythritol ester (Hercules Chemical Hercoflex 707), and a very high molecular weight polyester (Rohm and Haas Paraplex G-25). Again, in many cases, good to excellent Retention of Elongation properties were developed after both the 7 Day - 158°C and 60 Day - 136°C aging tests. The test results show DYTHAL®XL and TRIBASE*XL to be more effective in developing good retention of physicals with NTM or Hercoflex 707. The use of LECTRO 60®XL gave better retention of physical properties with the more basic lead sensitive polyester plasticizer.

Additional 125°C Penetration Resistance tests performed on 20 mil compression molded specimens sandwiched around a No. 20 AWG solid copper conductor showed that none of the formulations illustrated in Tables I and II could be used to meet UL Subject 758 specifications for Penetration Resistance. The conclusion was reached that the use of only ultra-high molecular weight PVC resins or high molecular weight plasticizers, although significantly upgrading the resistance to thermal decomposition would, however, fail to improve the resistance to flow properties required at temperature ratings higher than 105°C.

In view of the above data, it became apparent that the base formulation would have to be further modified to include materials capable of improving the resistance to flow in order to maintain dimensional stability under load at 125°C. The easiest and least costly approach was to increase the solids level of the formulation either by reducing the plasticizer concentration or by adding an inert filler media.

Table III shows the results of a study used to develop the levels of plasticizer and filler required to meet UL 125°C Penetration Resistance requirements using two flat 20 mil compression molded slabs sandwiched around a No. 20 AWG solid copper conductor to simulate a wire construction. The base formulation included an ultra-high molecular weight PVC, Geon 109EP (100) with LECTRO 60®XL (10) as the stabilizer component. The plasticizer (NTM) and filler (Mistron Vapor Talc) were varied at concentrations ranging from 40 - 50 phr and 30 - 80 phr, respectively. Mistron Vapor Talc was selected as being representative of a low cost silicate filler system having a low specific gravity and being well known for its reinforcing contribution in many plastic and elastomeric applications.

The data demonstrated that a minimum pass Penetration Resistance rating could be achieved with a NTM/Mistron Vapor Talc level of either 40/50 or 50/60. Lower specific gravity fillers could be used at lower loadings due primarily to their greater volume effect. In contrast, the lower efficiency, higher molecular weight polymeric plasticizers could also serve to reduce high temperature flow properties.

Having established a definite plasticizer/filler level range in order to meet UL Penetration Resistance at 125°C, the next step was to investigate the retention of physical properties of the filled formulations after 7 Day - 158°C oven aging. Commercially available fillers such as the clays, micas, talcs, silicas, calcium carbonates, and certain metal oxides were investigated at the levels necessary to develop insulation compounds capable of meeting UL Penetration Resistance requirements at 125°C. Without exception, all compounds tested resulted in unsatisfactory Retention of Elongation properties.

The silicate fillers, including clay, mica and talc, often used as extenders in 60° - 90°C rated wire insulation, were observed to drastically reduce the retention of physical properties after oven aging.

The use of coated and uncoated calcium carbonates also resulted in formulations with very poor retention of physical properties. In the case of the carbonate fillers, increased plasticizer absorption by the filler fraction may also be considered as a factor contributing to poor retention of physicals after aging.

Fibrous asbestos fillers, although possessing excellent reinforcing properties, were also found to be excessively contaminated with iron, a well known catalyst for PVC degradation. For this reason, no further evaluation was performed on the asbestos family of fillers.

* Trademark of N L Industries, Inc.

In view of this data, it became obvious that the use of a truly inert, low cost filler component was essential in order to develop an UL rated 125° C PVC electrical insulation. Additional studies were conducted to develop a new stabilizer-filler component capable of providing resistance to both thermal degradation and to deformation under load at elevated temperatures. The net result has been the discovery of a unique class of fillers instrumental in the development and marketing of LECTRO®125. This product is a proprietary lead-barium sulfo-silicate complex useful as a stabilizer-filler single package component for high temperature PVC electrical insulation. Because of a pending patent application, we are unable to disclose the composition of this material at this time.

Let us now examine the performance of this class of fillers and, in particular, the filler component of LECTRO®125, termed proprietary filler (A), versus the other previously discussed filler additives. A base formulation consisting of Geon 109 EP (100), NTM Plasticizer (50), with a total stabilizer-filler level of 70 phr, was chosen. The stabilizer portion was equal in type and level to that employed in LECTRO®125. The filler level was also set equal to that found in LECTRO®125, but the type varied. All tests were performed on 20 mil compression molded specimens.

The results, as given in Table IV, clearly demonstrated the effectiveness of the LECTRO®125 filler component (A) in developing PVC insulation capable of meeting both UL 7 Day - 158°C Retention of Elongation and Penetration Resistance at 125°C. Although all filler systems investigated developed sufficient resistance to deformation to meet UL Penetration Resistance requirements at 125°C, only the insulation compound containing the LECTRO® 125 filler component (A) was able to surpass the 65% Retention of Elongation requirement after 7 Day -158°C aging. Proprietary fillers (B) and (C) also showed significant improvements in retention of physical properties after aging versus the commercial filler products.

Unfilled High Temperature Vinyl Compounds

There are several areas where the resistance to deformation may be waived while maintaining high temperature aging requirements. Penetration Resistance, for example, need not be a requirement for thin walled (5 mil) high temperature rated vinyl insulation. An additional area would include the use of 125°C rated vinyl compounds as primary insulation protected by an outer non-polymeric jacket.

Subsequent investigations into the above application areas have resulted in the development of LECTRO®XPL-125, a high potency lead stabilizer component designed for use in high temperature rated, unfilled, vinyl insulation where resistance to deformation is not mandatory, or may be accomplished through the use of cross-linked PVC systems.

The data given in Table V demonstrates the excellent thermal aging characteristics developed from both 20 and 5 mil slab specimens utilizing LECTRO®XPL-125. The data also show that easier to process lower molecular weight PVC resins, and higher efficiency, lower molecular weight plasticizers may be employed with LECTRO®XPL-125 in forming heat resistant insulation.

LECTRO®125 in Wire Insulation

Based on the principles and guidelines outlined previously, four 1/32-inch wire insulations were compounded with LECTRO®125 into pellets and extruded over a No. 20 AWG solid copper conductor using a Davis Standard 2-inch diameter, 20/1 L/D extruder. The type of materials evaluated and their levels are described in Table VI. These are economical thermoplastic PVC compounds. Raw material costs, based upon 14 cents per pound high molecular weight PVC resin, are 21 to 27 cents per pound, dependent upon plasticizer type. The wire constructions were tested in accordance with UL Subject 758 as follows.

Physical Properties

Table VII compares the physical properties before and after 7 Day - 158°C oven aging and 4 Day - 100°C oil immersion. The oven aging data clearly demonstrates the effectiveness of LECTRO® 125 in conjunction with both an ultra-high molecular weight PVC resin and a low volatility plasticizer system in developing optimum retention of physicals. The oil immersion data, although showing all wire constructions with satisfactory properties, nevertheless, indicate that maximum performance is developed through the use of the permanent, polyester plasticizer systems.

Deformation Under Load

Penetration Resistance data were developed through the use of a vibration-free oven environment at both 125° and 132°C. A vibration-free condition was established to minimize the effect of vibrational "saw-through", while the higher temperature was selected to illustrate differences between the wire constructions. The results as given in Table VIII again clearly demonstrate the effectiveness of LECTRO®125 combined with an ultra-high molecular weight PVC resin and a high

molecular weight plasticizer system in developing optimum "cut-through" resistance, particularly at 132°C.

As anticipated, all the constructions were also observed to develop excellent 121°C Deformation Resistance and Room Temperature Slow Compression properties, well in excess of the minimum requirements.

Flexibility

Table IX shows the flexibility properties of wire insulation compounded with LECTRO®125 at both high and low temperature environments. All four wire constructions were found to easily meet the Cold Bend test requirement without cracking, at -10°C. Cables employing the high efficiency, monomeric plasticizer systems such as Normal Trialkyl Trimellitate or Dipentaerythritol Ester failed to develop cracks even at the lowest test temperature, -45°C. The construction using a medium molecular weight polyester plasticizer exhibited cracking at -35°C.

Subjecting the cables to UL 1 Hour - 158°C Heat Shock and 7 Day - 158°C Flexibility tests revealed the excellent thermal resistance developed through the use of LECTRO®125. All constructions exhibited no rupture or cracking after each test (Table IX).

Flame Resistance

Wire insulations using LECTRO®125 in conjunction with Antimony Oxide are found to meet UL Subject 758 Horizontal Flame specifications. The test cables were observed to be self-extinguishing and non-dripping (Table X). The non-dripping characteristic can be attributed to the ability of LECTRO®125 to fill the polymer matrix and thus reduce the flow of the flammable plasticizer component.

Vertical Flame tests are often employed to evaluate the flame resistance characteristics of wire insulation on a more critical basis. Tests of this type are more severe than the Horizontal method in that they create an up-draft effect which tends to propagate the flame beyond the point of initial contact.

Figure 1(a-c) is used to illustrate a modified version (twisted pair) of the Vertical Flame test given in Insulated Power Cable Engineers Association (IPCEA) Publication S-61-402. In this test, a flame has been applied to the base of two vertically supported wire insulations which have been twisted together to form a bundle. The flame is applied for 15 seconds, then removed for an additional 15 seconds. This is repeated for a total of five applications. A paper indicator flag is placed 10 inches above the flame ignition point to determine the flame travel distance. Failure of the specimen occurs when 25% of the flag is destroyed and/or a maximum after-burn time of 60 seconds following each ignition.

Table X and Figure 1(a-c) show that insulations made with LECTRO®125 are self-extinguishing after flame removal. Figure 1c shows that the unburned sections can be readily separated, thus demonstrating the good resistance to flow and non-dripping characteristics of the test specimens.

Table X also shows the excellent flame resistance properties of compression molded 125 mil slabs as measured by means of the ASTM D-2863 Oxygen Index Test. This test determines the lowest possible oxygen content at which a specimen continues to burn after ignition. The oxygen content is measured in percent and termed "Oxygen Index". The higher the value, the greater the non-combustible nature of the test specimen. Materials with Oxygen Indices greater than 27 are arbitrarily classified as self-extinguishing. All insulations are seen to possess Oxygen Indices above 29.

Electrical Properties

Table XI shows the results of the UL Subject 758 Voltage Breakdown test before and after 7 Day - 158°C oven aging. All cables were found to develop excellent resistance to dielectric failure before and after oven aging.

Electrical insulations employing LECTRO® 125 were also found to develop excellent direct current Insulation Resistance properties at room temperature and after 1 and 7 Days at 136°C. The highest values were observed after the 7 Day - 136°C aging cycle and are due to the removal of the electrically conductive plasticizer components through volatilization.

The use of polymeric plasticizer systems to develop optimum resistance to thermal aging and deformation properties, nevertheless, often lead to the formation of insulation with reduced electrical resistivity characteristics. Plasticizer polymerization techniques, in many instances, serve to introduce permanent ionic structures which tend to lower the overall electrical performance of the PVC insulation.

Table XII shows that the volume resistivity of high temperature PVC insulation containing a polymeric plasticizer system can be significantly upgraded through the use of low levels of electrical

grade clays. Clay levels of 15 phr are seen to improve the volume resistivity twenty to forty fold.

There are instances where electrical cable systems may be subjected to sudden high current surges for a short period of time, often exceeding the listed current rating. When this situation occurs, the result is a very rapid increase in conductor temperature, in many cases leading to severe insulation decomposition. Figure 2 illustrates the effect of LECTRO®125 in improving the current overload of PVC electrical wire insulation. Wire insulations using LECTRO®125 were observed to endure a 33 ampere alternating current ($\approx$500°F conductor temperature) twice as long as a 105°C rated PVC insulation.

Conclusions

The data presented demonstrate that economical thermoplastic PVC compounds can be formulated and extruded to form wire constructions capable of meeting tentative UL Subject 758 specifications for 125°C rated electrical insulation. Certain component requirements must be met to form optimum 125°C rated electrical compounds. These are found to be the use of a very high molecular weight PVC resin; low volatility, high molecular weight plasticizer system; and the use of a new lead stabilizer-filler additive, LECTRO®125. Wire insulations formulated on these principles and utilizing LECTRO ®125 are seen to possess outstanding resistance to thermal degradation and flow at high temperatures, as well as excellent flame-resistance and electrical properties. Special applications have been found for a high potency lead stabilizer system, LECTRO® XPL-125, particularly in the areas demanding high temperature performance, exclusively, with no requirements for resistance to flow or deformation.

It is anticipated that PVC insulation using LECTRO®125 may also find use in the 75° - 105°C range either as thin walled primary or jacket construction. Additional applications may exist in the "under the hood" automotive market where resistance to heat, flame and electrical overloads are critical requirements.

Edward J. Augustyn was born in 1938 in New York City and received his Bachelor of Science degree in Mathematics from the City College of New York in 1967 and his Master of Science degree in Engineering Science (Physics) from the Newark College of Engineering in 1972. He has been a member of N L Industries' Pigments and Chemicals Division Plastics Department for eleven years, and is currently a Project Leader responsible for the development of materials for electrical insulation applications.

Edward L. White holds a B.S. degree from Queens College and a Masters degree in Chemistry from Polytechnic Institute of Brooklyn. He has been affiliated with N L Industries, Inc. (formerly National Lead Company) since 1945. Primary interests during this period have been stabilizers for PVC, wax lubricants, and fire retardant additives. He has published several papers and holds patents, with several pending, in these areas. He is currently Technical Director of the Pigments and Chemicals Division of N L Industries, Inc.

TABLE I

Effect of PVC Molecular Weight on Physical and Deformation Properties

PVC Resin	Stabilizer	Tensile Strength Orig. psi	Tensile Strength Retention, %	Elongation Orig. %	Elongation Retention, %	Plast. Loss % of Plast.	Penet. Resist.(1) Pass/Attempts
		Aged 60 Days at 136°C					125°C
Geon 101EP	DYTHAL®XL	3360	90	310	63	21	0/3
Geon 109EP		3760	85	290	76	20	0/3
Geon 101EP	LECTRO 60®XL	3480	73	320	57	18	0/3
Geon 109EP		3730	74	305	60	17	0/3
		Aged 7 Days at 158°C					125°C
Geon 101EP	DYTHAL®XL	3440	70	335	77	14	0/3
Geon 109EP		3650	91	275	92	15	0/3
Geon 101EP	LECTRO 60®XL	3150	81	300	64	14	0/3
Geon 109EP		3800	80	320	69	13	0/3

Formulation: PVC (100), Hercoflex 707 (50), Stabilizer (10), Bisphenol A (0.5)

(1) UL specification Subject 758 calls for the application of a 350 gram load by means of a 90° wedge plunger to an insulated wire for 10 minutes at 125°C before insulation failure. Laboratory experiments involved the use of two compression molded 20 mil slab specimens sandwiched around a No. 20 AWG solid copper conductor to simulate a wire construction. Specimens were conditioned 5 minutes prior to application of load to develop thermal equilibrium. After conditioning, the test was performed with the oven blower motor turned off to maintain a vibration-free environment.

TABLE II

Stabilizer/Plasticizer - Effect on Physical and Deformation Properties

Plasticizer	Stabilizer	Tensile Strength Orig, psi	Tensile Strength Retention, %	Elongation Orig. %	Elongation Retention, %	Plast. Loss % of Plast.	Penet. Resist.[1] Pass/Attempts
		Aged 60 Days at 136°C					125°C
NTM	LECTRO 60®XL	3560	89	315	59	28	0/3
	DYTHAL®XL	3460	103	280	80	31	0/3
	TRIBASE*XL	3540	95	315	58	32	0/3
Hercoflex 707	LECTRO 60®XL	3500	83	285	61	18	0/3
	DYTHAL®XL	3720	86	315	65	20	0/3
	TRIBASE*XL	3480	87	280	82	19	0/3
Paraplex G-25	LECTRO 60®XL	3320	82	250	72	18	0/3
	DYTHAL®XL	3510	100	250	55	30	0/3
	TRIBASE*XL	3560	99	215	75	32	0/3
		Aged 7 Days at 158°C					125°C
NTM	LECTRO 60®XL	3730	81	295	77	23	0/3
	DYTHAL®XL	3690	97	295	86	22	0/3
	TRIBASE*XL	3650	97	340	71	26	0/3
Hercoflex 707	LECTRO 60®XL	3750	78	300	67	13	0/3
	DYTHAL®XL	3920	83	280	82	17	0/3
	TRIBASE*XL	3890	82	315	85	19	0/3
Paraplex G-25	LECTRO 60®XL	3740	73	235	92	12	0/3
	DYTHAL®XL	3520	92	195	84	17	0/3
	TRIBASE*XL	3530	87	225	77	20	0/3

Formulation: Geon 109EP (100), Plasticizer (50), Stabilizer (10), Bisphenol A (1)

(1) See Table I for method of test.

*Trademark of N L Industries, Inc.

TABLE III

Effect of Filler and Plasticizer Levels on Penetration Resistance at 125°C[1]

Mistron Vapor Talc Level (PHR)	NTM Plasticizer Level	Pass/Attempts
0	40	0/3
30	40	2/3
40	40	2/3
50	40	3/3
60	40	3/3
40	50	2/3
50	50	2/3
60	50	3/3
70	50	3/3
80	50	3/3

Formulation: Geon 109EP (100), LECTRO 60®XL(10), Plasticizer and Filler level (as shown)

(1) See Table I for test method.

TABLE IV

Effect of Fillers on the Physical Aging Properties of Electrical Insulation Compounds

Filler	Tensile Strength Orig, psi	Tensile Strength Retention, %	Elongation Orig, %	Elongation Retention, %	Plast. Loss % of Plast.	Penet. Resist.[1] Pass/Attempts
	Aged 7 Days at 158°C - 20 Mil Slab					125°C
Proprietary Filler (A)	3327	86	247	69	23	3/3
Proprietary Filler (B)	2657	102	170	51	31	3/3
Proprietary Filler (C)	3237	93	250	50	22	3/3
Titanium Dioxide	3587	93	247	45	26	3/3
Glass Spheres 5000	2567	87	210	44	23	3/3
Zirconium Silicate	3753	103	258	39	29	3/3
Cab-O-Sil M-5	2790	133	142	35	37	3/3
Mistron Vapor Talc	2730	119	210	31	29	3/3
No. 33 Clay	2733	164	134	30	29	3/3
Silene EF Calcium Silicate	2553	120	35	29	40	3/3
Hydrated Alumina	3100	109	187	27	23	3/3
Mistron Vapor Talc - Calcined 2 Hrs. at 950°C	2717	152	195	22	31	3/3
BSH Whiting - Coated $CaCO_3$	2177	118	200	15	30	3/3
Chemcarb 11 - Uncoated $CaCO_3$	2427	116	207	14	30	3/3
Winnofil S - Coated $CaCO_3$	2450	133	170	7	44	3/3

Formulation: Geon 109EP (100); Normal Trialkyl Trimellitate Plasticizer (50); Stabilizer - type and level employed in LECTRO®125; Filler-level equal to that employed in LECTRO®125. Stabilizer-filler level = 70 phr.

(1) See Table I for Penetration Resistance test method.

TABLE V

Effect of LECTRO®XPL-125 on Physical Properties of Vinyl Insulation

	Original versus 7 Day - 158°C Aged Slab Specimens							
PVC Resin	Geon 99	Geon 99	Geon 99	Opalon 660	Opalon 660	Opalon 660	Geon 99	Geon 99
Plasticizer	NTM	Hercoflex 707	Santicizer 409	NTM	Hercoflex 707	Santicizer 409	Hercoflex 707	Santicizer 409
	20 Mils						5 Mils	
Tensile Strength, Orig. (psi)	3337	3400	3690	2910	2837	2547	2750	3082
% Retention	85	85	75	88	85	95	104	93
Elongation, Orig. (%)	290	278	273	283	290	275	237	250
% Retention	93	91	90	82	86	91	77	73
Plasticizer Loss, % of Plast.	18	12	10	15	14	11	21	19

Formulation: PVC (100), Plasticizer (50), LECTRO®XPL-125 (13), Antimony Oxide (3), Stearic Acid (0.1)

TABLE VI

Composition of Wire Insulation Made with LECTRO®125 (1)

	A	B	C	D	E
PVC (I.V. = 1.34 - 1.43) (2)	100	100	100		100
PVC (I.V. = 1.10 - 1.19) (2)				100	
LECTRO®125	70	70	70	70	75
Normal Trialkyl Trimellitate (NTM)	50			50	
Hercoflex 707		50			
Santicizer 409			50		
Plastolein 9789					50
Antimony Oxide	3	3	3	3	3

(1) Solid No. 20 AWG copper conductor with 1/32-inch insulation.

(2) I.V. = Inherent Viscosity as per ASTM D-1243-66, Method A.

TABLE VII

Physical Properties - 1/32-Inch Insulation over No. 20 AWG Solid Copper Conductor

	A	B	C	D (1)	E (2)	
Primary Variable	NTM	Hercoflex 707	Santicizer 409	PVC (I.V.= 1.1 - 1.19)	Plastolein 9789	U.L. MINIMUM
	Orig. versus 7 Day - 158°C Aged					
Tensile Strength, Orig. (psi)	2621	3019	2683	2558	3168	1500
% Retention	106	90	89	109	98	70
Elongation, Orig. (%)	275	310	292	270	291	100
% Retention	62	74	71	52	89	65
Plasticizer Volatility, % of Plast.	26	20	13	43	14	-
	Orig. versus 4 Day - 100°C ASTM No. 2 Oil Immersed					
Tensile Strength, Orig. (psi)	2621	3019	2683	2558	-	-
% Retention	115	105	115	101	-	50
Elongation, Orig. (%)	275	310	292	270	-	-
% Retention	76	85	91	87	-	50

(1) 50 PHR NTM Plasticizer

(2) 75 PHR LECTRO® 125

TABLE VIII

Deformation Under Load Properties - 1/32-Inch Insulation over No. 20 AWG Solid Copper Conductor

Primary Variable	A NTM	B Herco-flex 707	C Santi-cizer 409	D [1] PVC (I.V.= 1.1-1.19)	E [2] Plasto-lein 9789	U.L. MINIMUM
	Penetration Resistance - Minutes to Failure					
125°C						
Trial 1	>12.0	>12.0	>12.0	4.9	>12.0	10
Trial 2	>12.0	>12.0	>12.0	2.6	>12.0	10
Trial 3	>12.0	>12.0	>12.0	4.0	>12.0	10
Average of 3 Trials	>12.0	>12.0	>12.0	3.8	>12.0	10
132°C						
Trial 1	0.6	0.9	3.2	0	12.0	-
Trial 2	1.0	0.6	3.7	0	11.6	-
Trial 3	0.5	1.1	2.3	0	12.0	-
Average of 3 Trials	0.7	0.9	3.1	0	11.9	-
	Deformation Resistance, 1 hour at 121°C, 500 Gram Load					
Thickness Ratio, Final/Orig.	0.63	0.75	0.74	0.65	0.79	0.50
	Slow Compression at Room Temperature					
Average Force to Cause Failure, lbs.	112	148	155	100	-	50

(1) 50 PHR NTM Plasticizer

(2) 75 PHR LECTRO®125

TABLE IX

Flexibility Properties - 1/32-Inch Insulation over No. 20 AWG Solid Copper Conductor

Primary Variable	A NTM	B Herco-flex 707	C Santi-cizer 409	D [1] PVC (I.V.= 1.1-1.19)	U.L. MINIMUM
	Cold Bend Test - 1/4" Mandrel				
Cracking after 1 hour at °C	<-45 [2]	<-45 [2]	-35	<-45 [2]	-10
	Heat Shock Test - 3/32" Mandrel				
Cracking after 1 hour at 158°C	None	None	None	None	None
	Flexibility Test - 3/16" Mandrel				
Cracking after 7 days at 158°C	None	None	None	None	None

(1) 50 PHR NTM Plasticizer

(2) No cracking or rupture at lowest possible laboratory cold box temperature.

TABLE X

Flame Resistance Properties - 1/32-Inch Insulation over No. 20 AWG Solid Copper Conductor

	A	B	C	D [1]	E [2]	
Primary Variable	NTM	Herco-flex 707	Santi-cizer 409	PVC (I.V.= 1.1-1.19)	Plasto-lein 9789	
	Horizontal Flame Test - UL Subject 758					U.L. MINIMUM
Rate of Burning, Inches per Minute	Non Burn.	Non Burn.	Non Burn.	Non Burn.	Non Burn.	<1"/Minute
Dripping Characteristics	None	None	None	None	None	None
	Vertical Flame Test - Twisted Bundle - Bottom Ignition					Maximum Value
After Burn Following Flame Removal (Secs.)						
1	0	0	0	< 2	0	60
2	0	0	0	< 2	0	60
3	0	0	0	< 2	0	60
4	3	0	0	3	0	60
5	0	0	<2	< 2	< 2	60
Burn Length (Inches)	4.5	4.5	4.5	5	4	
Condition of Flag, % Destroyed	No Change	No Change	No Change	No Change	No Change	25
Fusion of Unburned Insulation	Nil	Nil	Nil	Nil	Nil	-
	Oxygen Index ASTM D-2863, 125 Mil Slab Specimens					
125 Mil Slab Specimens	31.0	31.0	32.8	30.4	36.0	-

(1) 50 PHR NTM Plasticizer

(2) 75 PHR LECTRO®125

TABLE XI

Electrical Properties - 1/32-Inch Insulation over No. 20 AWG Solid Copper Conductor

	G	F	E	D	
Primary Variable	NTM	Herco-flex 707	Santi-cizer 409	PVC (I.V.= 1.1-1.19)	U.L. MINIMUM
	Dielectric Strength, Orig. vs. 7 Day - 158°C Aged				
Average breakdown, volts - Orig.	36,600	34,500	24,300	35,300	2,000
% Retention	80	87	105	84	50
	Insulation Resistance [1] - Megohms per 1000 Feet				
1 Day at 25°C	160	380	85	155	1.5
1 Day at 136°C	46	41	27	31	0.01
7 Days at 136°C	1100	825	975	600	0.01

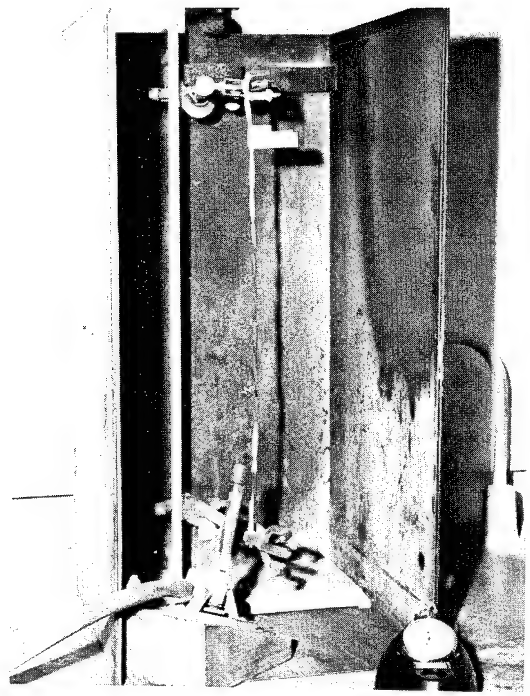
(1) Insulation covered with a close woven untinned copper braid.

Figure 1

Modified IPCEA Vertical Flame Test

(a)

(b)



(c)

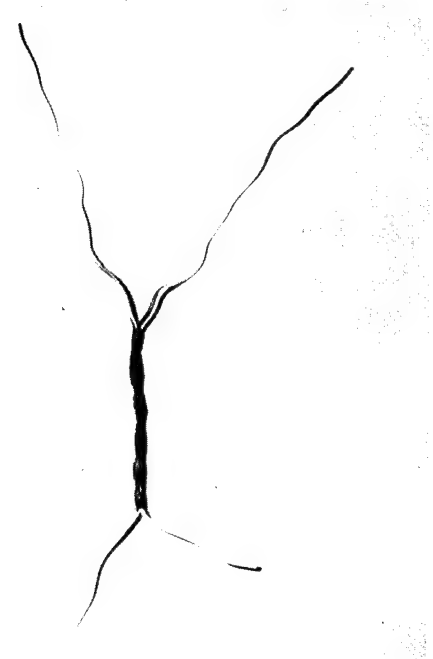


Figure 2

Current Overload Test - 33 Amperes (A.C.) on 1/32-Inch Insulation - No. 20 AWG Conductor

MINUTES TESTED

UL 105°C Rated   Developmental 125°C

1 2 3   1 5 6

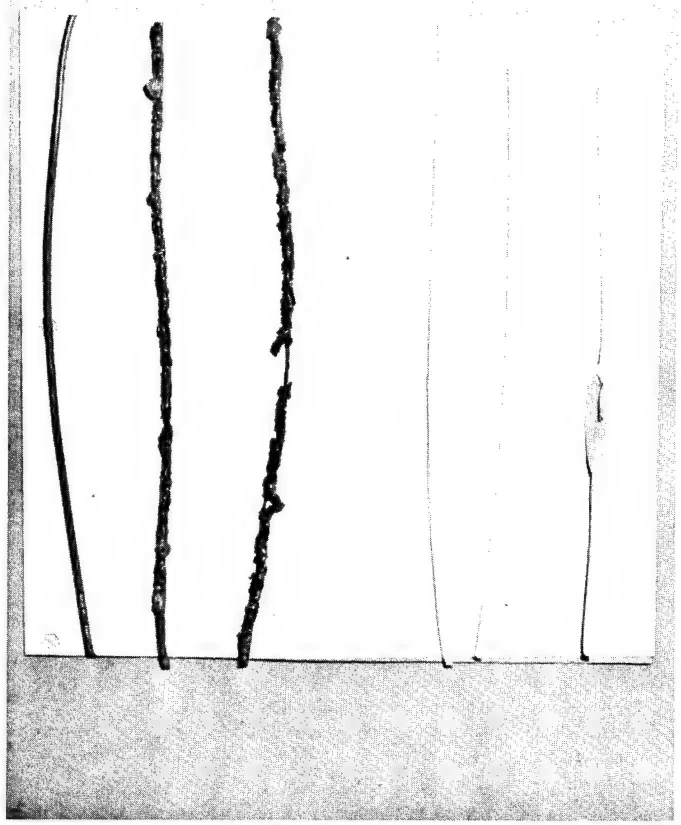


TABLE XII

Electrical Properties of Clay-Filled High Temperature Insulation

PHR Level			Volume Resistivity (1) at 70°C 10^{10} ohm-cm
Electrical Grade Clay	LECTRO®125	LECTRO®XPL-125	
0	80	-	9
7	70	-	62
15	60	-	199
0	-	13	3
7	-	13	64
15	-	13	136

Formulation: PVC Resin, Inherent Viscosity = 1.3^{+} (100), High molecular Weight Polyester Plasticizer (50), Other Components (as shown).

(1) Tests performed on 40 mil slab specimens using a Sticht 20 million megohmeter (500 volts D.C.output).

TEFZEL®* ETFE FLUOROPOLYMER: TEMPERATURE RATING AND FUNCTIONAL CHARACTERIZATION

J. C. Reed and J. R. Perkins

PLASTICS DEPARTMENT
E. I. Du Pont de Nemours & Co. (Inc.)
Wilmington, Delaware

Tefzel® ETFE fluoropolymer is rated at 150°C after a 10,000 hour aging program. Arrhenius plots of physical properties and actual performance tests on wire were used for this determination.

Summary

We described the properties of Tefzel® ETFE fluoropolymer two years ago at the 1970 Symposium. We stated then, based on early aging data, that we believed the material would probably qualify for a 150°C rating. We now want to report the results of studies conducted specifically to confirm this temperature rating for a wire insulation of Tefzel® and to verify the general level of properties after long-term aging.

The determination of a rating is always difficult and generates controversy, so we decided to arrive at a rating with two independent series of long-term tests. One was directed at physical properties and the other at performance.

We first looked at <u>physical properties</u>, tensile strength, and elongation. We used the Arrhenius method of IEEE Standard No. 1 and UL's definition of the temperature index as that temperature at which the material retains 50% of its original property measurement after 20,000 hours.

We then devised <u>two functional tests</u>--a "3/4" successive mandrel bend test" and a "1 time-1X bend after aging"--to establish mechanical performance. The rating would be the temperature at which at least 50% of all specimens would pass the two wrap tests after 10,000 hours. In addition, we checked dielectric strength, cut-through, and weight loss throughout the 10,000 hours aging up to 180°C.

<u>Our conclusions are:</u>

1. 150°C is a realistic rating for Tefzel® 200 as a wire and cable insulation.

2. The dielectric strength and cut-through resistance are unaffected, and weight loss is minimal after 10,000 hours at 180°C.

*Du Pont's registered trademark for its ETFE fluoropolymer resins.

Background

Tefzel® ETFE fluoropolymer is a copolymer of ethylene and tetrafluoroethylene in a roughly 25/75 weight or 50/50 molecular ratio. It was first made public in January, 1970, and has been available in developmental quantities since then. It has been fully commercial since June, 1972. A new plant at Parkersburg, West Virginia, is on-stream.

The technical and commercial development of this material has been exciting and rewarding. As a wire and cable insulation, it is already in use in electronic, aircraft, computer, and industrial applications where it is covered under a variety of specifications.

Table I briefly lists typical properties. More details can be found in our paper presented in the 1970 Symposium.

Experimental Method and Results

Samples

The wire samples were chosen at random. All were 20 AWG, 10 mil wall single extrusion made at different times of various colors under varying processing conditions from different resin lot numbers to insure the test results would represent "typical" quality wire coming off a processor's production line. A total of 3,000 specimens were tested in the program.

TABLE I

TYPICAL PROPERTIES OF TEFZEL®

	Values	Units	ASTM Test
MECHANICAL			
Specific Gravity	1.70		D792
Tensile Strength, 73°F (22.8°C)	6500 (456)	psi (kg/sq cm)	D638
Yield Strength, 73°F (22.8°C)	4000 (281)	psi (kg/sq cm)	D638
Elongation 73°F (22.8°C)	150*	%	D638
Flexural Modulus 73°F (22.8°C)	200,000 (14,020)	psi (kg/sq cm)	D790
Flex Life, MIT 9 mils (0.23 mm), 180° bend	30,000	flexes	
Impact Strength (Notched Izod) 73°F (22.8°C)	No break	ft-lbs/in.	D256
-65°F (-53.9°C)	$>$20 $>$ (10.9)	ft-lbs/in. (kg-m/cm)	D256
Coefficient of Friction, $>$10 fpm (3.05 m/min.); 100 psi (7.03 kg/sq cm)	0.4		
Hardness, Durometer	D75		D1706
Rockwell	R50		
THERMAL			
Melting Point, DTA Peak	520 (271)	°F (°C)	
Service Temperature	302(150)	°F(°C)	
Flammability, UL Rating	SE-O		
Heat Distortion @ 60 psi (4.2 kg/sq cm)	220(104)	°F(°C)	D648
@264 psi (18.5 kg/sq cm)	160(71)	°F(°C)	D648
Coefficient of Linear Thermal Expansion, 32-350°F (0-177°C)	9.5×10^{-5} (17×10^{-5})	in./in./°F (cm/cm/°C)	D696
Low Temperature Embrittlement	$<$-150($<$-101)	°F(°C)	D746
CHEMICAL			
Water Absorption	$<$0.02	%	D570
Weather & Chemical Resistance	Outstanding		
ELECTRICAL			
Dielectric Constant @ 10^2 Hz	2.6		D150
@ 10^3 Hz	2.6		D150
@ 10^6 Hz	2.6		D150
Dissipation Factor @ 10^2 Hz	0.0006		D150
@ 10^3 Hz	0.0008		D150
@ 10^6 Hz	0.005		D150
Dielectric Strength, 10 mils (0.25 mm)	$>$2000($>$ 80)	volts/mil(kv/mm)	D145
Volume Resistivity	$>10^{16}$	ohm-cm	D257
Surface Resistivity	$>10^{14}$	ohm-sq	D257

*Elongations between 100 and 300% are achieved with varying methods of manufacture, sample size, and preparation.

The choice of that particular size was made because of convenience and internal reference to other work where we had used that construction as a standard.

Physical Properties - Arrhenius Method

The tests were run for 10,000 hours at 135, 150, 165, and 180°C. The temperature rating can be arrived at using the Arrhenius relationship following IEEE Standard No. 1. We used the Underwriters' Laboratories' criterion for choosing the temperature index or rating as the temperature at which 50% of a given physical property is retained after 20,000 hours. Figures 1 and 2 demonstrate the test results on room temperature tensile strength and elongation, respectively. The graphs allow the level of these properties to be easily noted after any given time and temperature of exposure.

Using these charts, one sees that half values of tensile strength and elongation are reached in 20,000 hours at 175 and 160°C. The determining figure, as with most materials, is elongation. Our 150°C rating figure is consistent with those results.

Retention of Mechanical Performance

To demonstrate that Tefzel® 200 displays satisfactory mechanical performance at 150°C, we designed and carried out two very demanding functional tests during and after a series of exposures up to 10,000 hours at the same 135, 150, 165, and 180°C temperatures.

The first test is described as a "3/4" SUCCESSIVE MANDREL BEND TEST". The procedure is as follows. Each specimen is wrapped on a 3/4" mandrel and aged on that mandrel for a predetermined time. At the end of the exposure, the wire on the mandrel is wet-proof tested at room temperature. If it passes, the wire is unwrapped from the mandrel and wrapped in the opposite direction. It is again wet-proof tested; if it passes, it is returned to the oven for another exposure. This procedure is repeated on each specimen until it fails. Integrated exposure times were 64, 128, 256, 496, 1,000, 2,500, 5,000, and 10,000 hours.

Figure 3 summarizes the results of these tests. Note that 70% of the specimens had passed the 10,000 hour test at 150°C and 40% were still surviving at 165°C. Thus the 150°C rating is indicated.

The second test is the "1 TIME-1X MANDREL AFTER AGING TEST". The procedure is simple. First, an exposure to time and temperature is selected. The wire is first aged in straight form for half of the test time. It is then wrapped about its own diameter at room temperature and returned to the oven for the second half of the exposure. It is then wet-proof tested at room temperature as mandrel wrapped. A second proof test is made after unwrapping. The specimen is then discarded.

The results are summarized in Figure 4. At 150°C, 75% of the specimens survived at the end of the test and at 165°C, 50% survived.

The 150°C rating is seen to be a reasonable one and in agreement with the philosophy that the temperature rating is that temperature at which no more than 50% of the specimens fail in the given 10,000-hours time.

Wire Characteristics After Aging 10,000 Hours

TABLE II

LOSS OF WEIGHT WITH TIME AND TEMPERATURE

Aging Temperature °C	Annual Rate of Weight Loss* (g/g)
135	0.0006
150	0.0014
165	0.003
180	0.006

*Initial loss of absorbed gases 0.0013 g/g at any elevated temperature.

The room temperature dielectric strength was unaffected after 10,000 hours aging at 180°C. The room temperature dynamic cut-through to failure as measured on an Instron with a .005" blade and a constant displacement of 0.2"/minute remained at 46.5 pounds (average) on samples taken before, during, and after 10,000 hours at 180°C.

Discussion of Results

The physical property and performance methods used to determine the thermal agree well. The performance tests were tougher than those usually given to insulation materials. Actual exposure for long-time periods to temperature around and above the "rated" temperature enhances the confidence of a user since users often have reservations about high temperature, short term, accelerated aging tests truly representing suitability in use.

How does one use this rating? Is Tefzel® limited to 150°C? No, Tefzel® can be used above 150°C. How high and for how long depends on what level of properties must be retained. This is for the design engineer to decide. When a user asks this question, it is often because he is looking for a 165, 180, or 200°C material. The next question is: Does the use require continuous or long-term use at that temperature? If it does, we would normally recommend Teflon®*. If the exposure is only short term, between 150 and 180°C, we would have to decide between Tefzel® 200, cross-linked Tefzel® 200, or our new resin, Tefzel® HT-2008.

*Reg. U.S. Pat. Office for Du Pont's fluorocarbon resins.

Cross-linking Tefzel®, like polyethylene or PVC, can enhance high temperature properties for the short term.

The new member of the Tefzel® family, HT-2008, on which we have preliminary data, also seems to better withstand short term temperature excursions to 200°C. Still, long term continuous use rating for Tefzel®, plain or cross-linked, should be 150°C using the same criteria we've described for Tefzel® 200.

Conclusion

We believe the 150°C rating is sound. In fact, it could be 155 or 160°C, so we are conservative. Where does that place Tefzel® among insulating materials? We've not tried to compare Tefzel® to other insulations. We shouldn't compare it to Teflon® because Teflon® is a special, truly "extraordinary" material which practically doesn't age within its use temperature range, so we'd have to compare it to other partially fluorinated materials like PVF_2, CTFE, and ECTFE; i.e., materials in the gap between 105 and 200°C. On balance, we think the overall comparison of the electrical, thermal, chemical, and mechanical performance of Tefzel® on wire would show Tefzel® favorably.

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Fig. 1

R. T. TENSILE STRENGTH TRADE – OFF AFTER AGING

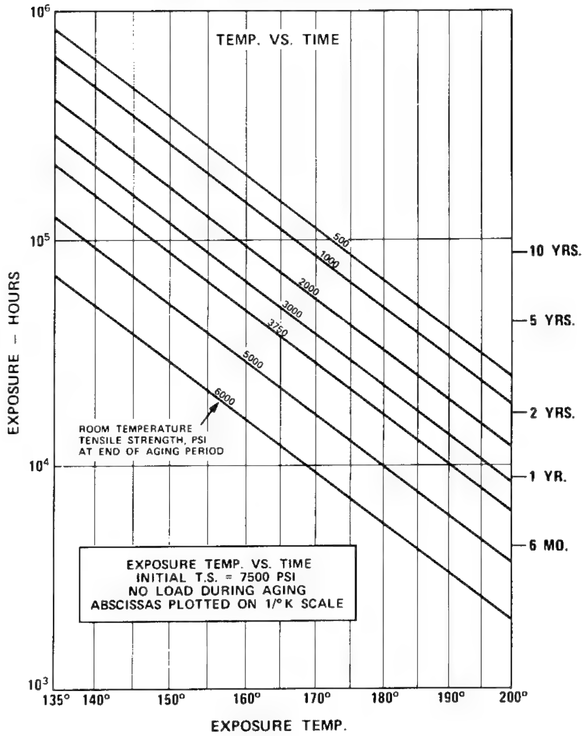


Fig. 2

R. T. ELONGATION TRADE – OFF AFTER AGING

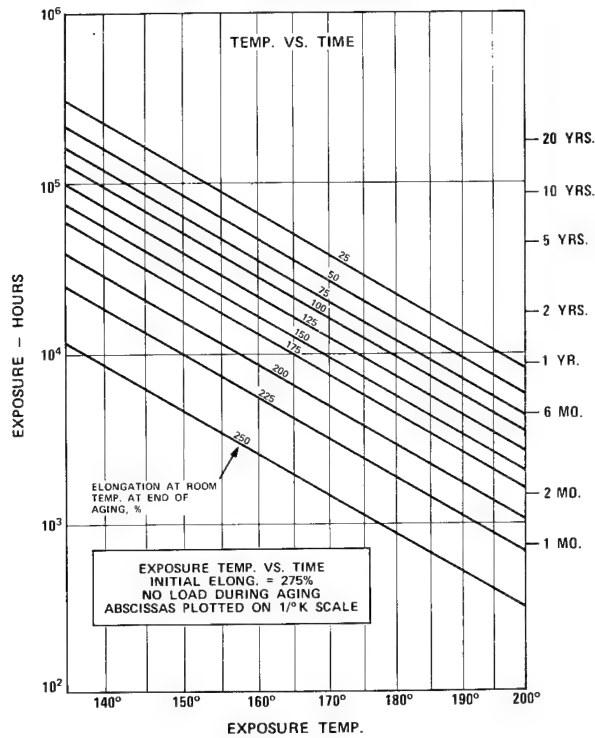


Fig. 3

SUCCESSIVE – 3/4" MANDREL HEAT AGING TEST

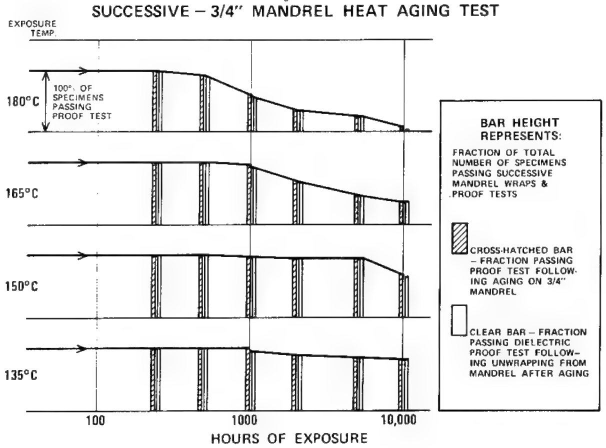
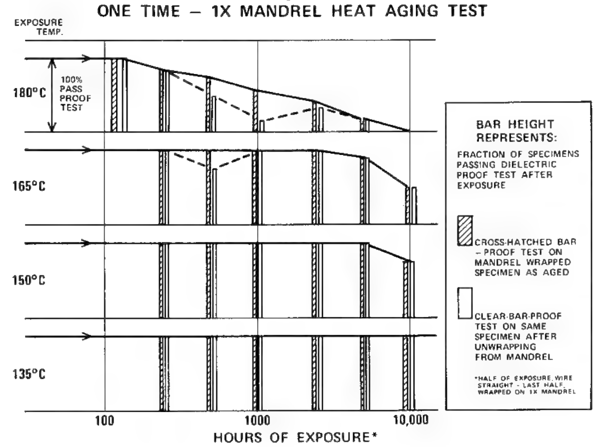


Fig. 4

ONE TIME – 1X MANDREL HEAT AGING TEST



700 SERIES CONNECTORS FOR ALUMINUM AND COPPER TELEPHONE CABLE CONDUCTORS

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Abstract

The design and performance of a new series of self-encapsulated, insulation piercing connectors for splicing and bridge-tapping two or three 17 - 26 AWG aluminum and copper telephone cable conductors are discussed. Consideration is given to the electrical, mechanical and environmental aspects of the problem.

Introduction

In the late 1960's, the Bell System began commercial use of aluminum conductor multipair cable as an alternative to copper. Economics and the assurance of a stable supply are incentives to use aluminum. The physical properties of aluminum create a new set of technical problems for manufacturing, placing, splicing and maintaining these cables. This paper is concerned with the field splicing problem, which has been a deterrent to expanded use of aluminum cable.

Laboratory tests showed that reliable, long term stable splices of 17 and 20 gauge aluminum conductors can be made with the B Wire Connector[1], Figure 1, if the conductor insulation is removed before splicing and the completed joints are encapsulated in polyurethane. The encapsulation provides necessary mechanical and corrosion protection. The B Wire Connector, which has been the Bell System standard for joining copper cable, makes reliable connections to paper, paper pulp and fine gauge plastic conductors without stripping insulation. Sharp tangs in the liner, as shown in Figure 2, penetrate the insulation to establish the contact. However, it is also necessary to remove the plastic insulation from heavy gauge conductors (19 and 22) because expansion of the insulation due to temperature variations degrades the quality of the contacts. Mixing the two-part polyurethane compound, and encapsulating the connectors, as shown in Figure 3, is time-consuming and very unpopular with the field construction forces. Thus, these two factors, stripping of insulation and post-encapsulation of the joints, provided strong incentives for developing an improved splicing method.

At about the same time aluminum cable became a commercial product, the waterproof cable development[2] reached the field trial stage. The conductor insulation is about 50% thicker on a waterproof cable to maintain the same capacitance as present non-filled cable. This requires that insulation be stripped from most conductors before joining with the B Wire Connector. The filling compound makes stripping even less desirable, thus, another demand was created for an improved splicing method.

The geometry and general design features of the 700 Connectors, which overcome the deficiencies of the B Wire Connector, are discussed in the next section. Following that are sections dealing with the contact element, and sealant used in the connector, installation tools, test results and summary.

700 Connectors

A new series of versatile connectors, coded by Western Electric as 700 Connectors, were designed to join small pair count, 400 pairs and smaller, aluminum and/or copper cables. Most 17 and 20 gauge aluminum and all waterproof cables used today in the Bell System are in this range.

The basic design of the 700 Connectors consists of a slotted-beam, metallic contact and a sealant in a transparent plastic

case. Two sizes were designed. The 700-3A is used to butt-splice any combination of two or three 17 through 26 gauge conductors, or bridge-tap up to two conductors to a third. The 700-2A, about two-thirds the size of the 700-3A, is used to butt-splice any two 19 through 26 gauge conductors, or bridge-tap one conductor to another. Bridge-tapping (half-tapping) is accomplished without cutting the existing conductor or disrupting service by dislodging the sidewall of the connector and slipping the existing conductor into a groove. No stripping is required regardless of conductor material, gauge or insulation (paper, paper pulp, polyethylene, polypropylene, PVC or irradiated PVC). Slip the conductors into holes of the body, press the cap over the body and a solder equivalent moistureproof connection is effected.

Exploded and assembled views of the 700-2A and 700-3A prototypes are shown in Figures 4 and 5, respectively. The blue plastic cap contains the metallic contact and a sticky sealant, which automatically encapsulates the connections. The clear plastic body receives the conductors, one in each hole, and positions them for connecting. Extended fingers in the body grip the conductors and isolate the contact area from mechanical disturbances. A thin membrane in the cap serves as a test point. This feature is intended to obviate the necessity for puncturing through the insulation to establish a test point, a practice particularly undesirable with aluminum conductor cable because of the greater potential for corrosion hazards and wire breakage.

The 700-3A Connector is in production at the Baltimore Works of the Western Electric Company and the 700-2A is scheduled for production in the near future. The production version of the 700-3A Connector, shown in Figure 6, is essentially the same as the prototype. The conductor grips were redesigned for faster installation, and the removable sidewall was molded in place to reduce manufacturing costs.

Contact Element

Since it is necessary to splice aluminum cables to copper cables, the contact element of the 700 Connectors had to be designed to join either or both conductor types in the same connector. The slotted-beam principle was considered because of its desirable features and proven reliability with copper cables. Insulation is pierced, and both insulation and oxide films are wiped from the contact areas as a conductor is forced into the slot. Elastic energy stored in the deflected beams provides contact pressure.

Making and maintaining reliable, low-resistance pressure contacts to aluminum is exceedingly more difficult than to copper. The aluminum is covered with a hard insulating oxide film that when removed, reforms almost instantly in air. The problem is how to rupture this film and establish a gas-tight contact to the pure metal.

Contact surfaces are normally plated to prevent growth of oxide films and provide a gas seal. However, laboratory tests showed that tin plated, slotted-beam contacts, which have been traditionally used with copper conductors, were unstable with aluminum. A new solution was needed.

Basic contact studies[4] conducted in the Wire Joining Group at Bell Laboratories demonstrated that stable low-resistance contacts can be made to aluminum if one of the surfaces was indium plated. Further tests showed that stable contacts could be made to both aluminum and copper conductors with indium plated slotted-beam connectors. Indium's high ductility, low yield strength, non-strain hardening, and surface wetting properties are responsible for the good performance.

As a result of the plating breakthrough, an indium plated slotted-beam contact element was chosen for the 700 Connectors. The contact, shown in Figures 4 and 5, is a thin, U-shaped strip of phosphor bronze. Narrow slots cut into the legs of the "U" form a number of cantilever beams. When the connector is pressed, each conductor is forced into two contact slots providing higher reliability through redundancy.

However, metallographic studies of the contacts revealed an undesirable characteristic of indium; copper diffuses into indium to form a hard, brittle alloy consisting of 40% copper and 60% indium. This was of concern because it might have influenced the shelf life of the connectors and caused long-term degradation of completed splices. However, a determination of the alloy growth rates and mechanical stresses in the alloy at the contact interface revealed there would be no problems with the 700 Connectors as long as the contact plating was 0.0003 inches minimum.

Another difficult problem associated with splicing aluminum conductors is penetrating tough insulations, such as polypropylene, at low temperatures. The H-11 aluminum conductor can be drastically deformed without breaking through the insulation films. The unique insulation piercing entrance of the 700 Connector

contact overcomes this problem.

Sealant

The sealant is intended to provide corrosion protection and prevent low insulation resistance (IR) by excluding moisture and gases. The present 700 Connectors are moistureproof but not fully immersible for extended periods of time. The IR of a small percentage of those immersed in tap water can be expected to degrade from typically greater than 10^{12} ohms to about 500 megohms in a week, while the IR of others will not degrade in six months. Twenty thousand megohms is the lower limit of IR specified for dry connectors. These connectors provide a second line of defense in all buried splices; in air core cable they will prevent circuit failures due to water entering a sheath break until repairs can be made on a routine basis.

A moisture resistance test outlined in Table I simulates the most severe environmental conditions expected in ready-access terminals, which are located flush with or above grade level. The 700 Connectors survived these tests without degradation of IR, evidence of any corrosion, or physical damage or increase in resistance.

Polyethylene-polybutene (PE-PB) compound was chosen for the sealant in the 700 Connectors after experimenting with numerous commercial and proprietary compounds. PE/PB is nearly ideal; it readily adheres to all of the plastic insulation used; can be displaced at all environmental temperatures, but doesn't drip at 160°F; is reasonably impermeable to water with a high insulation resistance and dielectric strength; and is not harmful to humans. On the negative side, PE/PB is a moderate stress cracker of DYNH polyethylene, used in standard cracking tests. However, under similar test conditions and in wire wrap tests, it has been found that insulation-grade polyethylene is not cracked by PE/PB.

Installation Tools

The intended use of the 700 Connectors, small pair count cables and service wire terminations, suggested a simple, rugged, inexpensive hand tool. It became clear in the development that a high force was required to close the connectors when joining large conductors at low ambient temperatures. A simple pliers was not sufficient. The increased viscosity of the sealant and the increased cut-resistance of polypropylene insulation at low ambient temperature account for most of the force requirements. While the 700 Connector is not as sensitive to how the pressing force is applied as some other connector designs, the pressing tools were designed to give a nearly parallel press and feedback to the operator that he has completed the press.

A modified vise-type plier, shown in Figure 9, was chosen after field testing several designs. It is coded the E Connector Presser, AT-8597. Undoubtedly, as the usage of the Connector increases, other designs will be made available to help the craftsman do his job faster with less effort, such as a tool with a magazine to hold a number of connectors. But for the present, the E Connector Presser meets the basic tool requirements; it is simple, rugged and inexpensive.

Laboratory Tests

A number of mechanical and electrical tests were performed in the laboratory to characterize the connector. These tests were designed to determine if the connector-tool system will provide reliable long-term connections in the telephone plant environment. Cable splices were made in large walk-in test chambers to determine how reliable the connector-tool system would be at various temperatures. After the laboratory tests verified the reliability of the system, field tests were conducted to study the craft-system interface, i.e., do craftsmen working in the field get the same results as those obtained in the laboratory?

Mechanical Tests- Spliced conductors were stressed to determine if they could withstand the mechanical handling associated with splicing and rearranging splices. A tensile strength of 85% of the mean conductor strength, and 10 each 180° torsional rotations and bends without breaking the wires are considered reasonable limits for satisfactory field handling. Twenty-five samples of each conductor gauge and metal were tested. All exceeded the requirements except for a few 20 gauge aluminum samples which had tensile strength as low as 76%.

The aluminum splices were given extra handling to simulate severe field conditions, because of the higher notch sensitivity of aluminum and the occurrence of a few samples with lower tensile strength. Completed cable splices were very tightly wrapped, unwrapped, conductors separated, reformed into a bundle and very tightly rewrapped a minimum of four times. After these tests, some splices were "shaped" by striking the splice with a wooden club, duplicating an unrecommended practice that sometimes occurs. No wire breaks or insulation damage occurred. As a result of these tests and those above, the 700 Connector splices of both copper and

aluminum were considered mechanically sound.

Contact Resistance - Since 1963, it has been the objective of the Bell System that all cable splices be soldered or solder equivalent. Further, quality soldering methods have a reliability of only one bad joint in 10,000. Therefore, any solder equivalent system must provide a low-resistance, long-term, stable contact under dry circuit conditions ($\leq$ 50 millivolts), and have a failure rate equal to or less than one in 10,000.

Laboratory tests were designed and conducted to determine if connections properly made with the 700 Connectors were solder equivalent. Typically, the contact resistance of the 700 Connectors is about 0.1 milliohm and by our criterion, the resistance of one contact in 10,000 should not be greater than 1.0 milliohm after aging. Contact resistance greater than this indicates conduction through films and/or extremely small metallic contacts, both of which have a high tendency to become unstable. We analyzed the resistance distribution of the test samples statistically to estimate the one in 10,000 level.

Samples of all conductor combinations normally joined were subjected to temperature cycling; high-humidity temperature cycling; and stress relaxation. The thermally induced mechanical disturbances were largest with the temperature cycling, which cycled between -40° and 140°F, maximum limits normally expected in the telephone plant. The high-humidity temperature cycling stressed the vapor resistance of the connections. Aluminum joints are particularly sensitive to corrosion induced by moisture. The stress relaxation tests were used to obtain a quick measure of contact degradation due to relaxation of the aluminum or copper wire. Since the connector contact element is made of stress-relieved phosphor bronze, it is known not to relax more than 8-10% in service. The stress relaxation test is not as representative of actual service conditions as the other tests, but it gives results in a much shorter time. In this case, it showed that tin plated slotted-beam connectors aged poorly when joining aluminum conductors, a fact verified later by the other tests. Table I lists the parameters for each test.

The test configurations necessarily include about 2.0 inches of joined conductor in the measurements, which accounts for practically all of the resistance measured. For this reason, the measuring set had to have a high resolution and repeated accuracy to detect the changes in the contact resistance. The resolution and accuracy of the measurements for these tests were $\pm$ 15μ ohms. Table I lists the parameters for each test.

The results of the environmental aging tests were excellent; all wire types (aluminum, copper and copper-steel) and gauges (17, 20 and 24 aluminum; 19 - 26 copper; and 20 copper-steel) satisfied the solder equivalent criteria. Figures 7 and 8 are typical resistance plots for the test samples. These figures show the contact resistance aging to be nil after more than 1400 cycles. Further, the distribution of the resistances is a very good fit to the log-normal distribution. Thus, by knowing the distribution, we can predict the performance of the connections at the one in 10,000 level. Because all of the samples were well behaved and were very good fits to the log-normal distribution, we could predict the performance of all connections at the one in 10,000 level with a high degree of confidence.

Dielectric Strength - The dielectric strength requirements are 5000 volts DC between connections or to ground. The 700 Conductors easily exceed this requirement and in tests for a special application the breakdown exceeded 9000 volts AC RMS.

Field Tests

Field trials with prototype connectors were held in several Bell System operating companies for splicing aluminum cable, both air core and waterproof. The trial sites were chosen to get a range of environmental conditions. Craft reaction was very favorable; the system is faster and easier than other methods requiring stripping and encapsulation. The error rates were found to be as low as other splicing methods.

Summary

The 700 Type Connectors are a new family of moistureproof connectors for splicing copper and/or aluminum telephone cables using a simple inexpensive plier-type tool. They make splicing easier and quicker than previously used methods requiring stripping of insulation and encapsulation. These connectors are especially applicable to splicing buried cables, air core or waterproof, 400 pair or less in size, and terminating service connections in ready-access pedestals, closures and buried terminals. Bridge-tapping is uniquely accomplished by dislodging the sidewall of the connector to provide access for the through wire.

The Western Electric Company has begun to supply the 700-3A Connectors, which will splice any three conductors, 17 through 26 gauge or bridge-tap up to two conductors to a third. The 700-2A Connector should be available in the near future. It is two-thirds the size of the 700-3A, and will splice any two wires 19 through 26 gauge or bridge-tap one conductor to another.

Acknowledgements

This work represents the contributions of many others at Bell Laboratories and their efforts are greatly appreciated. The authors would like to acknowledge especially Mr. J. J. Zalmans for his help with the environmental testing and Mr. J. P. Starace for his efforts on the E Connector Presser.

Tailoring the connector design for low-cost mass production has been a joint effort with the Western Electric Company. Mr. P. R. Gustin and others in the Engineer of Manufacture Organization of the Baltimore Works have all made substantial contributions to this work.

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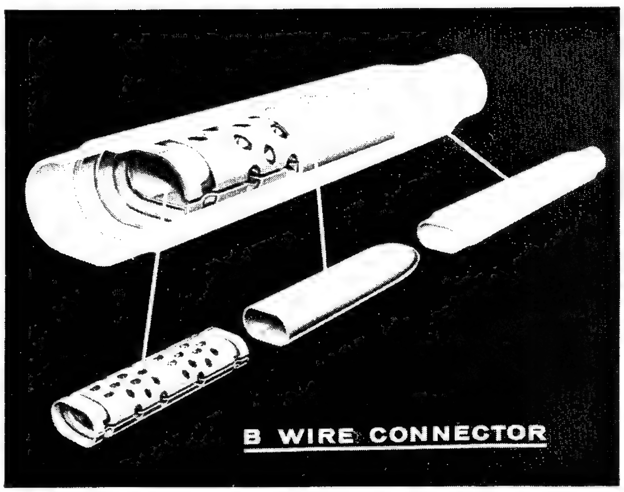
John P. Pasternak is an Associate Member of Technical Staff in the Connector Device Development Group of Bell Telephone Laboratories. He attended New York University and has been associated with the development of mechanical connector systems from 1957 to present.

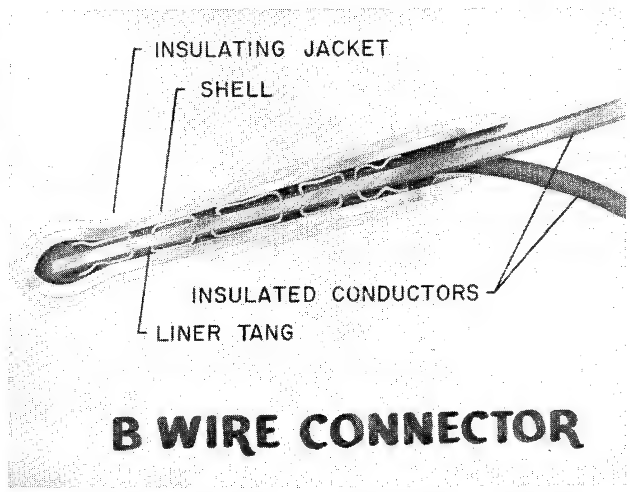
TABLE I

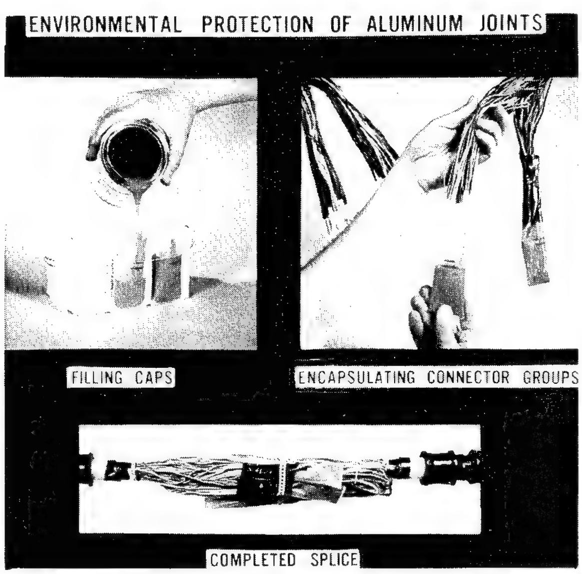
Environmental Tests - 700 Type Connector

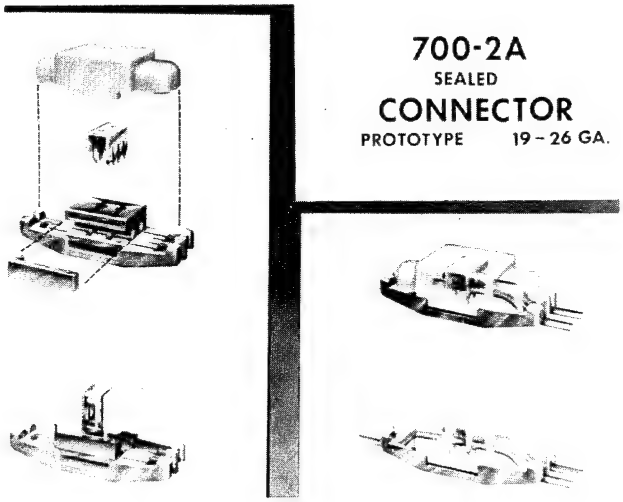
	Temp. Limits °F	Cyc. day	Dwell at Extremes (hrs.)	Resist. Meas. Intervals (cycles)*	Other
Temp. Cyc.	-40 to +140	12	.25	0, 8, 16,... 1024 N	
Temp-Humidity	+40 to +140	2	3.5	0, 37, 75, 150, 300 N	R.H maintained ≥ 95%
Moisture Resist.	-40 to +140	12	.25		Water sprayed on Connector to form ice*
Stress Relax.	244°	NA	Continuous	0, 1, 2, 4, 8, 16, 32 days	Mech. Disturbance Prior to Measurement

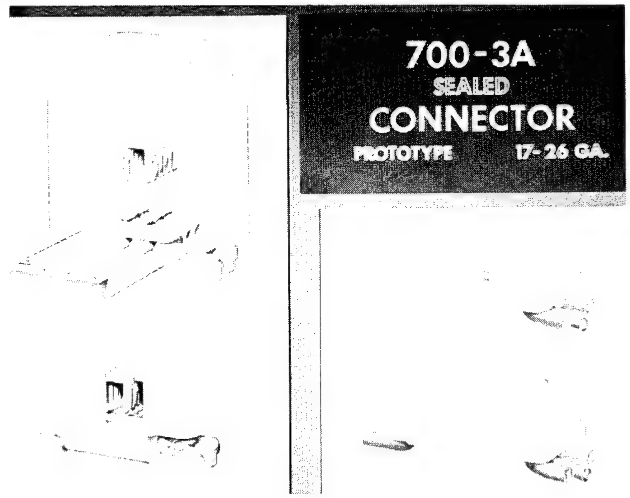
* All measurements made at room temperature.



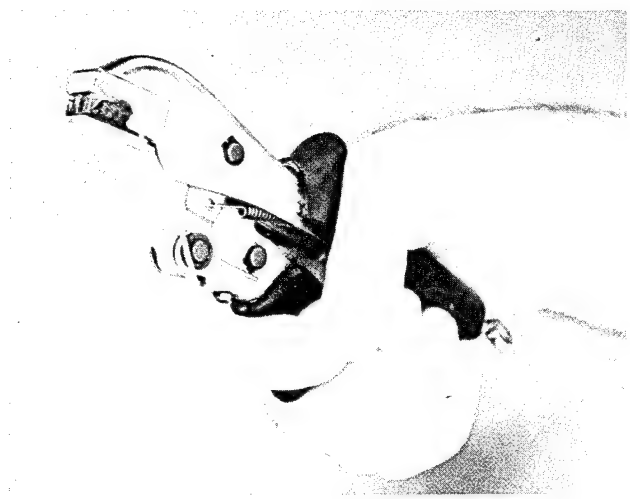








READY POSITION
700-3A CONNECT
SEALED 17-26 GA.



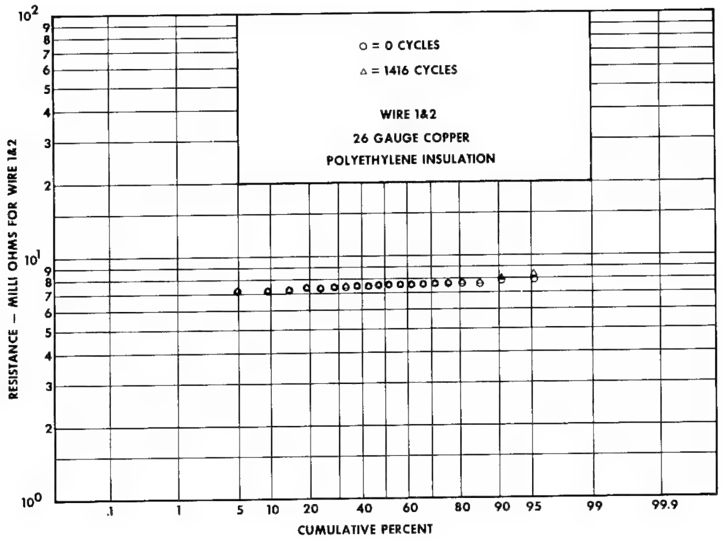


Figure 7 — 700-3A Connector - Temperature Cycled

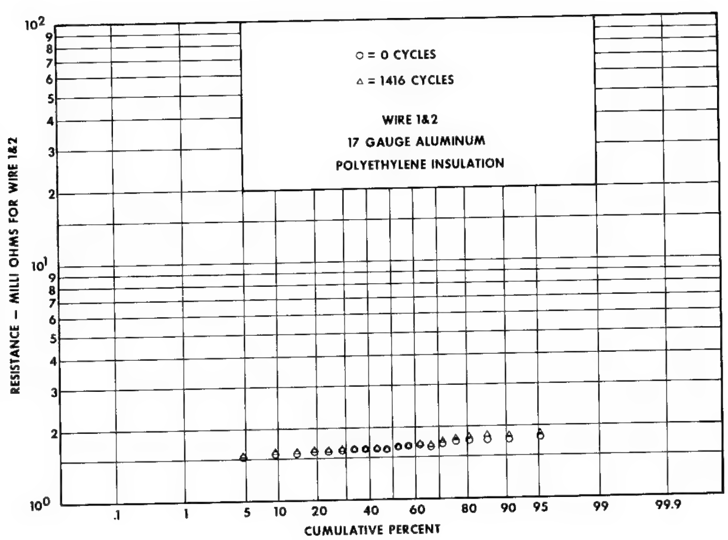


Figure 8 — 700-3A Connector - Temperature Cycled

A NEW "IN LINE" WIRE CONNECTOR FOR TELEPHONE CABLE SPLICING

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ABSTRACT

Successful wire connectors for the splicing of multi-pair telephone cable all have some or combinations of the following features: ability to make contact without removal of insulation; low resistance; good stability; compactness; low product cost; speed and simplicity of installation; and applicability to a variety of conductor sizes and insulation types.

Reliable Electric Company has developed a new connector which embodies all of the aforementioned features plus some unique advantages of its own.

The configuration of the connector is basically a channel shape and its construction consists of three elements, a hard, thin, inner metallic member having tanged contacts, a heavier soft outer metallic member and an insulating outer member which also serves as a link between adjacent connectors so as to form long chains.

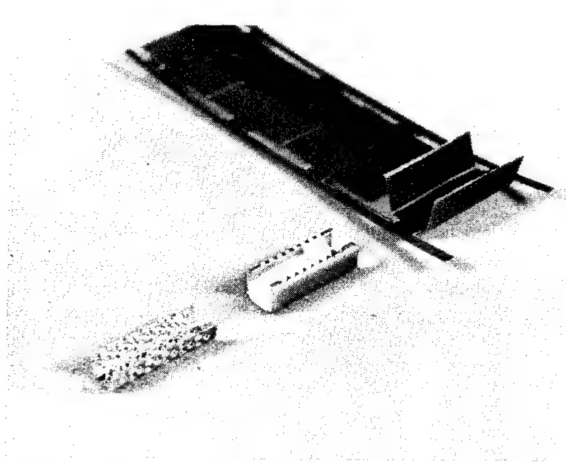

Fig. 1 Exploded view of Channel Connector.

Its "in line" splice capability allows it to be used with wrapped paper insulated conductors as well as plastic and pulp. Its smaller size reduces splice case bundle volume, it is capable of tap splices without interrupting subscriber service and can with a single size, accommodate 26 AWG through 19 AWG conductors without stripping the insulation.

A special automatic pneumatically powered splicing tool is used with the channel connector. This tool accommodates connectors in continuous belt or chain form supplied from reel or box. With one press of a button it automatically trims the conductor ends, shears the individual connector from the belt, crimps the connector to the conductors and feeds the next connector into position. The sheared tips of the conductors are automatically pulled inboard from the ends of the connector so as to expose no bare metal to potential shorting hazard.

BACKGROUND

In developing the new connector we at Reliable chose to apply the contact philosophy of the B-Wire connector, a concept with which we were very familiar, having been a manufacturer of this device for many years under license from Western Electric. In that product, a thin, hard, springy tubular insert with insulation piercing tangs is encased in a tubular outer shell of soft, heavier brass and an insulating sleeve covers the assembly.

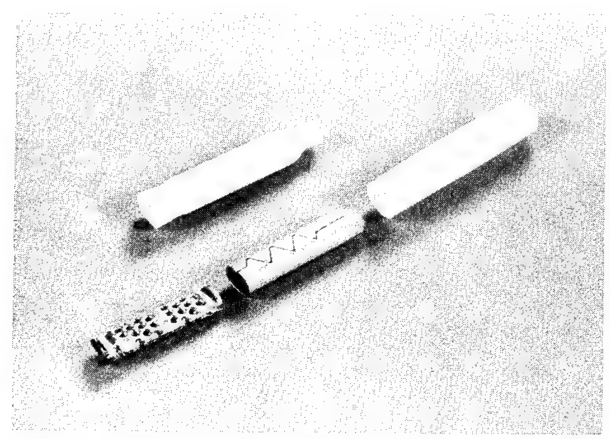

Fig. 2 Exploded view of B-Wire Connector.

In the splice, the hard insert member makes the electrical contact and the soft heavy outer shell retains the energy of the crimp preventing spring back.

With all its merits, the B connector is not ideally suited to all applications. It cannot be used in splicing

wrapped paper insulated cable because of the shiner problem which occurs when one of the two conductors in the splice is folded back. The wrapped paper tends to unravel in such cases sufficiently to possibly expose bare wire at the bend. (Fig. 3)

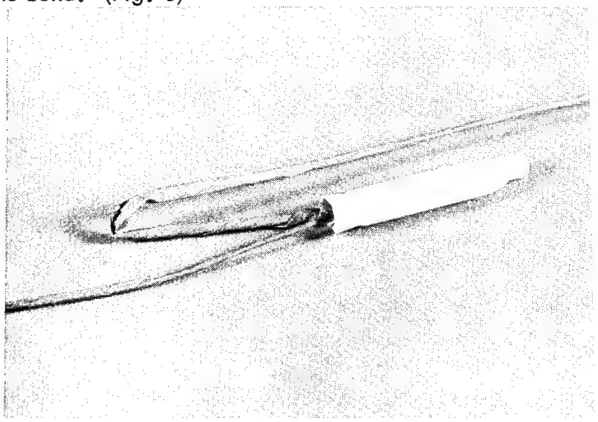

Fig. 3 B-Wire Connector with wrapped paper insulated conductor, showing shiner at bend.

The space consumed is also relatively large, both by the connector itself, plus the additional conductor material of the folded back wire member. Splicing speeds are limited due to the coordination required to insert the conductor into the rather small opening of the connector as well as the necessity of manually arranging the groups into orderly fold back bundles.

To overcome these drawbacks a new configuration was chosen. The choice was the channel shape. (Fig. 4)

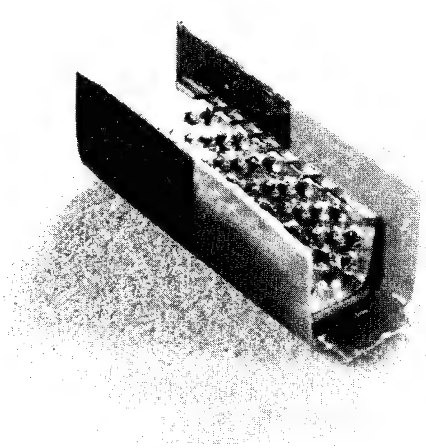

Fig. 4 Channel Wire Connector

The fold back and subsequent shiner problem in paper insulated cable is eliminated, since splices are now made "in line". Space is reduced by 53% in the volume of the connector itself. (Figs. 5, 6)

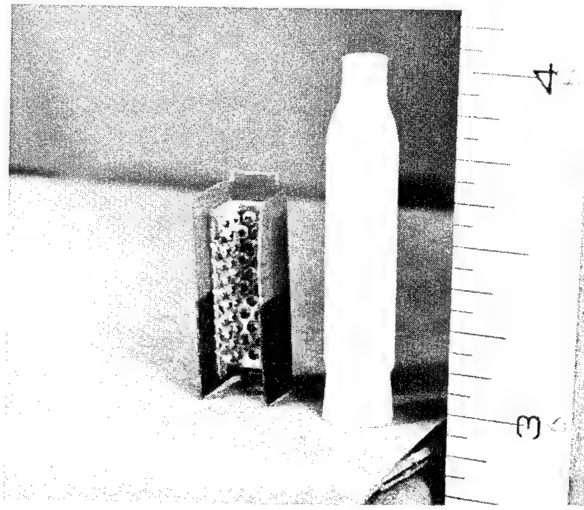

Fig. 5 Size comparison between Channel and B-Wire Connectors.

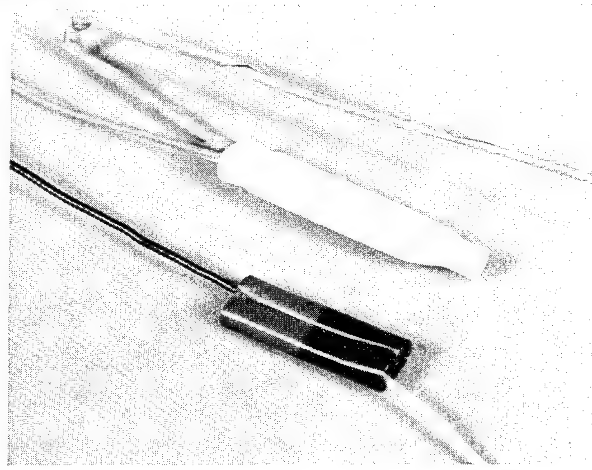

Fig. 6 Size comparison between Channel and B-Wire Connectors.

Splicing time and effort are reduced with the new automatic crimping tool developed for the connector. (Fig. 7)

CONNECTOR

As for the physical details of the connector, consider first, the insert. Here we use a tin coated phosphor bronze foil of .004 thickness in the spring temper. The phosphor bronze is perforated so as to form a series of four point tang clusters. Experimentation with various tang arrangements and spacings led to the eventual choice of a 71 tang group on an eleven by 6-7 matrix. (Fig. 8)

The foil is then formed into a channel. (Fig. 1)

The shell is made of soft red brass and is four times the thickness of the insert. The sides of the channel are terminated in small flanges which serve a dual purpose. They act as retainers to lock in the insert and they also abut one another in compression in the crimped condition so as to resist relaxation and opening up. (Figs. 9, 10)

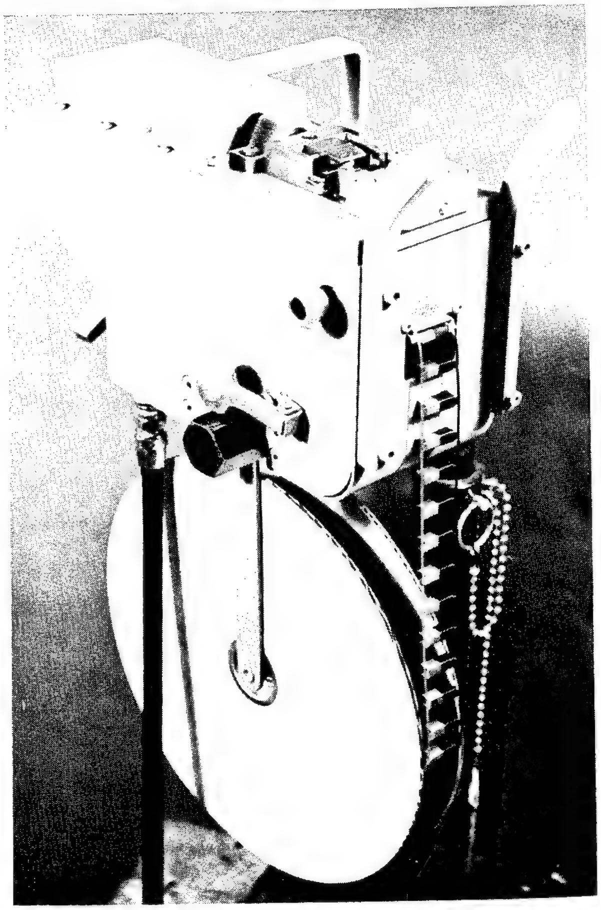

Fig. 7 Automatic crimping tool.

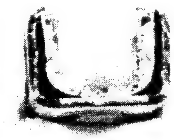

Fig. 9 End view of Channel Connector (uncrimped).

Fig. 10 End view of Channel Connector (crimped).

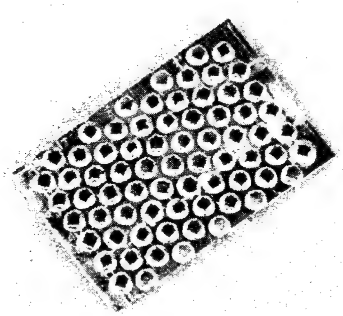

Fig. 8 Contact array on insert.

The insulator is Mylar polyester film. It is adhesive bonded to the brass shell in the form of a continuous belt. In this manner it serves as its own carrier strip. (Fig. 11)

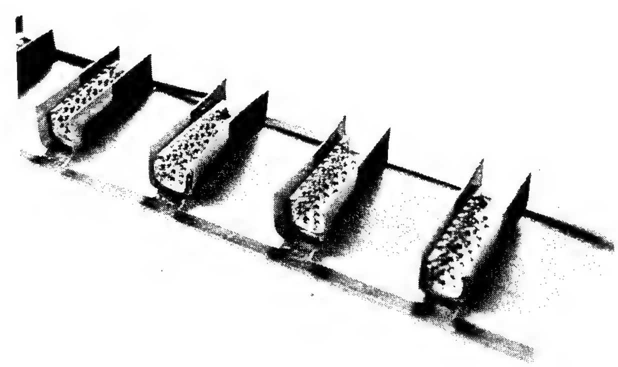

Fig. 11 Channel Connectors in strip.

Mylar was chosen for its excellent dielectric properties in thin section and for its outstanding crush resistance. Crush resistance is important in withstanding the high pressures of the crimping tool.

TOOL

A special tool has been developed to automatically crimp the connector. The connectors are belt fed from reels into the tool.

A manual control is provided for initial threading of the belt into the crimping head. (Fig. 12)

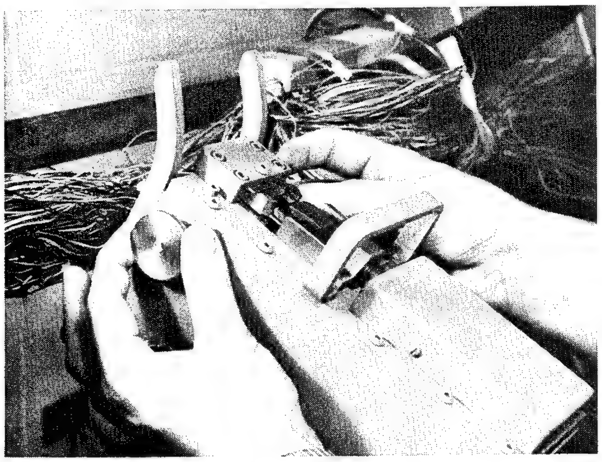

Fig. 12 Initial manual threading of connector strip into crimping tool.

The operator then secures the conductors in place within a pair of built in spring clamps. (Fig. 13)

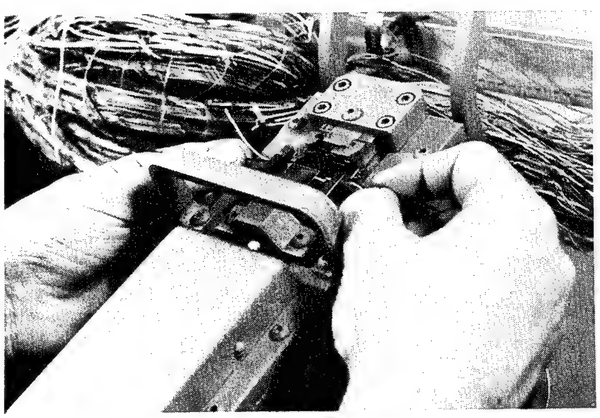

Fig. 13 Securing conductors in tool.

He now presses the trigger buttons (two are provided so that both hands are clear of the splice area), and

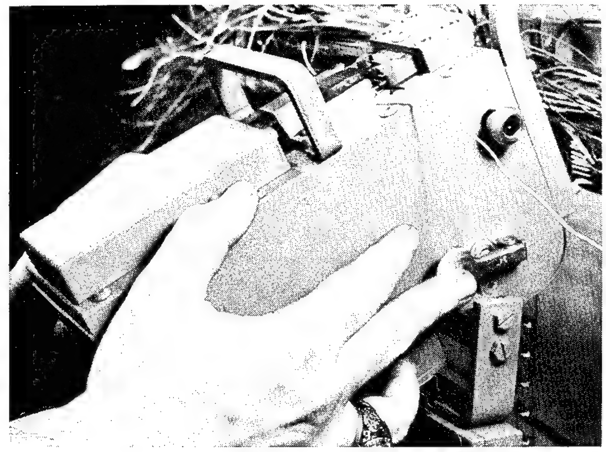

Fig. 14 Triggering crimping tool.

a pneumatically actuated ram moves toward the in place connector. The following actions now occur automatically in rapid sequence: cutting surfaces on the ram shear the excess conductor ends; the action of the machine components draws the sheared wire tips in from the ends of the connector so that no bare metal surfaces are exposed in the splice. (Fig. 15)

Fig. 15 Crimped connector showing sheared tip of conductor pulled in from end of connector.

The connecting web of the Mylar is sheared; the crimping dies form the connector into the completed splice; and the next connector is automatically fed into place. (Fig. 16)

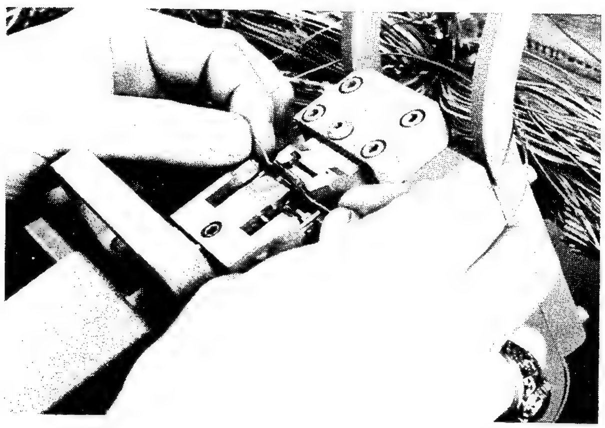

Fig. 16 Finished splice being removed from tool.

With this system we can provide not only two wire straight splices but also tap splice, three wire splices and four wire splices, all with the same connector and with the same crimping tool. (Fig. 17)

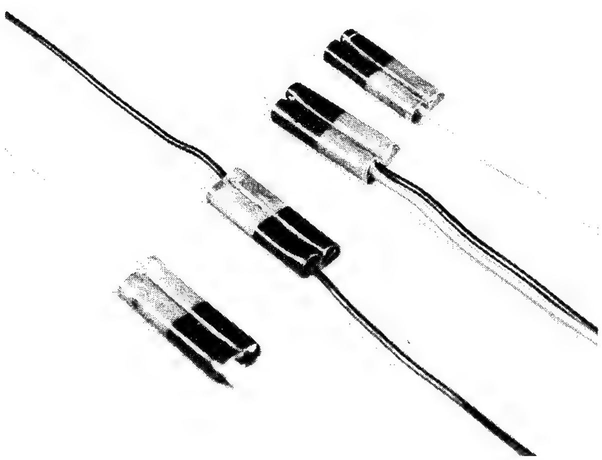

Fig. 17 From top to bottom: 2 wire, 3 wire, tap and 4 wire splices.

The range of cable sizes and splice types with the basic connector, tool combination is as shown in Table 1.

		2-Wire	Tap	3-Wire	4-Wire
26 AWG	PIC	x	x	x	x
	PAPER	x	x	x	x
24 AWG	PIC	x	x	x	x
	PAPER	x	x	x	x
22 AWG	PIC	x			
	PAPER	x	x		
19 AWG	PIC	x			
	PAPER	x	x		

Table 1.

In its crimped form the connector is compressed more at its center than at the ends. This is done to provide some relief at the point where the conductor emerges from the connector so as to prevent wire breakage. (Fig. 18)

Fig. 18 Side view showing maximum compression at center and relief at ends.

Another feature for assuring reliability is found in the flanges of the connector shell. The flanges are made with a sawtooth edge. This is done in order to avoid interference between conductors and the flange in the event of a conductor crossover in the splice (a particular possibility in tap and multi-wire splices.) (Fig. 1)

The sawtooth configuration allows the conductor to fall between the points of the teeth and thereby reduce interference with the crimping of the shell. In the event that one or more of the teeth should strike a conductor with its point, then its sharp shape would permit it to penetrate the insulator and act as a contact. In either eventuality a good crimp is produced.

The resistance characteristics of this device compare favorably with those of the standard B-Wire Connector.

In use, the crimping tool may be mounted on either of two mounting devices; a portable adjustable stand or a transverse carriage which moves horizontally in one inch increments along the length of the cable splice area. Figs. 19, 20. With either device the attitude of the tool can be varied from horizontal to vertical in 30° increments. This feature permits the operator to select the most comfortable position for any cable arrangement. (Fig. 21)

CONCLUSION

The Channel Wire Connector, crimping tool combination provides an efficient, reliable splicing system applicable to a wide range of cable sizes and constructions.

Its small size, good resistance characteristics and low cost should provide an attractive solution to the problem of splicing multi pair telephone cable.

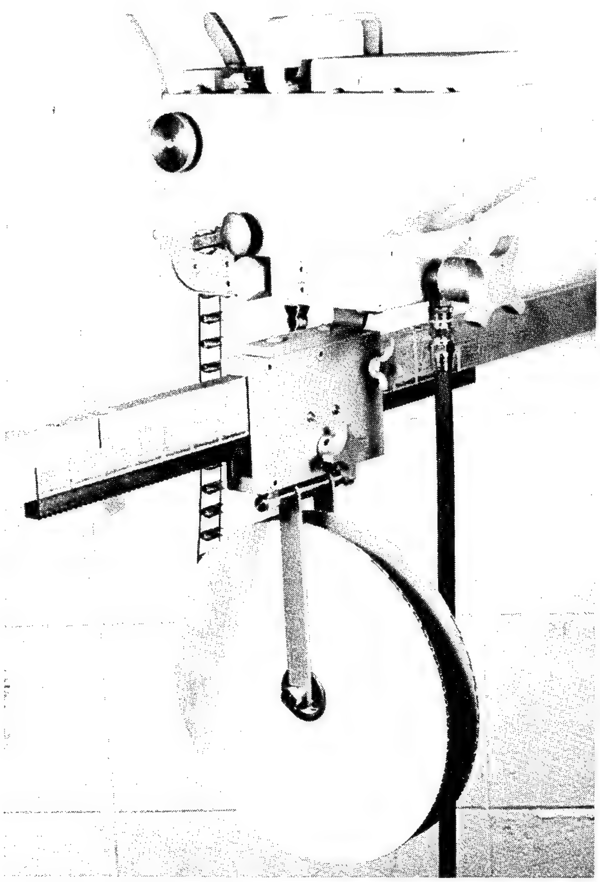

Fig. 19 Transverse carriage.

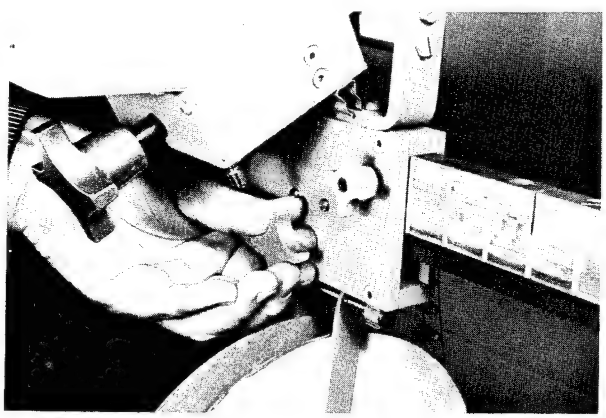

Fig. 20 Transverse carriage

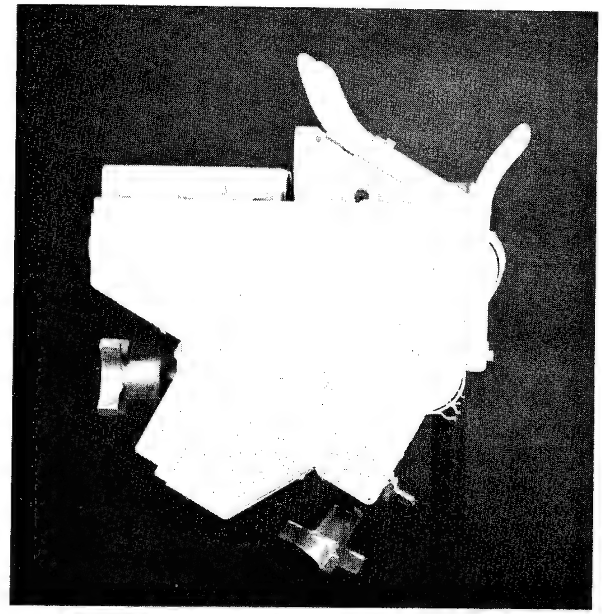

Fig. 21 Attitude adjustment of tool.

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In this capacity he has, since 1966, been active in the development of connecting devices, outside plant and station apparatus.

Previously he was a Member of the Technical Staff in the Research and Development Organization of the Teletype Corporation, Skokie, Illinois, where his work involved the development of printing telegraph components and systems design.

Mr. Golden was graduated with a PhB from the University of Chicago in 1949 and received a B.S. in Product Design from Illinois Institute of Technology in 1954.

He has been issued two patents in the field of telephony and presently has two more on application.

EQUIPMENT FOR FILLING PETRO-JELLY UNDER PRESSURE AND SHEATHING THE FILLED CABLE CORE

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Abstract

A new filling equipment has been developed based on a pressure filling method by using a tube system comprising various heated sections. Detailed description of the equipment is given. Results of tests on cable manufactured are stated. The electrical properties and the installation of the filled cables will be mentioned.

Introduction

Various methods are already well known for filling a cable core consisting of plastic-insulated conductors with petro-jelly so that the cable is sealed against the ingress of water in the event of damage to the cable sheath. Whilst making use of this available knowledge, equipment has now been constructed which is based on a new method of filling by means of pressure only and which also comprises all the necessary equipment for the lapping and sealing of the filled cable core before the application of the plastic sheath. It has already been in use for some time in the manufacture of fully filled communication cables.

Principle of pressure filling

First of all, a description is given of the pressure filling method using a tube system comprising various sections, through which the cable core to be filled is drawn (fig. 1).

At the inlet end of the tube system is a removable nozzle which is matched to the diameter of the cable core to be filled. This inlet end is water cooled. The tube section installed immediately after the inlet nozzle is fully exchangeable and water cooled. It is matched only approximately to the diameter of the cable core.

The liquid petro-jelly, which is heated in a storage tank to a constant temperature, is forced into the pressure tube. This tube is the next section in the system and has a large inner diameter (60 mm). The petro-jelly flows counter to the movement of the cable core which it fills. The excess petro-jelly flows back into the storage tank through an adjustable valve, which is used to set the desired overpressure. The petro-jelly filling of the cable core is further compressed in the tube section by means of the conical profile of the tube. This section is water cooled too. An outlet nozzle in the tube system with the same design as the inlet nozzle must be intensively cooled. This nozzle is the termination of the cooling system.

In order to provide a clearer illustration of the principle, the following parts have not been included in fig. 1: heating system for petro-jelly circulation, storage tank, tube system with temperature gauges and control equipment, etc.

Sheathing

The cable core filled in the tube system is provided during its further progress through the equipment with longitudinally applied paper tapes and sheathed with copolymer-bonded aluminium sheeting, which is also applied longitudinally. Further equipment seals the copolymer-bonded aluminium sheeting tube. The aluminium sheath is then corrugated in a special tool, so that the filling is thus subjected to additional compressing. An outer plastic sheath can be applied with any type of extruder. The extruder does not form part of the filling equipment.

Description of the pressure filling equipment

The equipment comprises all the components required for the filling and sheathing of cable cores. Figure 2 is an illustration of a complete filling plant as used in actual practice. It comprises two mobile units which are coupled together for operational purposes.

The first mobile unit contains in a frame a tank of about 600 l capacity for liquid petro-jelly. This tank and all the tubing between the tank and the pressure filling tube are equipped with a water heating system and forced circulation. Control equipment with a temperature gauge fitted in the tank guarantees stability of the petro-jelly temperature. An additional agitator in this tank and the pumping of the liquid petro-jelly during filling prevent any local heating.

A switching panel contains the operating elements and control indicators which are required for heating the petro-jelly and operation of the equipment: temperature selection switch, pump motor operating switch, pump motor regulator for setting the petro-jelly flow.

The pressure tube filling system is installed at a convenient working height on the long side of this unit. The control valves for the hot and cooling water circulation are also easily accessible. The spindles for the paper discs forming the cable core wrapping and the aluminium sheeting are accessible from the side. The discs can be quickly replaced. The unit occupies a floor space of approx. 3m x 1m; dead weight approx. 1.3 t.

The second unit, which is also mobile, contains all the guiding and shaping tools for applying the paper wrapping and shaping, bonding and corrugating the sealed aluminium sheath. All the shaping tools, which have to be exchanged when there is any change in the cable core diameter, are easily accessible and adjustable. The sheathing unit occupies a floor space of approx. 1.5m x 0.75m; dead weight approx. 0.3 t.

When installed, the entire equipment has a length of approx. 5.2 m, width approx. 1 m. In a production line it is installed in front of the extruder.

In order to heat the petro-jelly in the storage tank - for instance, after a production stop - only connection to the supply mains is necessary. Connection to the water supply and electrical connection to the second unit are not required until operation is re-started.

The hot water system needs filling only once and topping-up is only necessary at extended intervals. Petro-jelly can be topped up during operation; it must, however, have the processing temperature 73° C ± 2° C. Small quantities of liquid petro-jelly (small in relation to the amount still in the tank) can be filled into the tank at other temperatures.

Practical experience

The advantage of the new filling method is seen in the fact that the rapid circulation prevents any separation of the petro-jelly. The relatively high rate of flow of the liquid petro-jelly counter to the drawn-in cable core means that the latter is sufficiently heated. The petro-jelly can thus enter the interstices of the cable quads under pressure.

The undesired escape of petro-jelly is avoided through the cooling of the inlet tube sections in front of the pressure filling tube and the outlet nozzle. The outer surfaces of the filling equipment cannot become smeared with cooled petro-jelly, although filling is possible at overpressure up to 3 atmospheres, depending on the cable type.

The advantage of the equipment for filling petro-jelly under pressure and sheathing the filled cable core lies in the fact that the two units, which are joined together for actual operation only, are mobile and their space requirements very modest. The easy operation of the entire plant and its adaptability to cable cores of different diameters offer further advantages.

Depending on the number of pairs, operation rates up to 40 m/min can be reached with this pressure filling equipment, which has been specially developed for filling subscriber cables up to 100 pairs with 0.4 mm diameter of conductor.

Product control

Petro-jelly for the new filling method only has to meet the well known requirements such as are stipulated, for instance, in specification 72 TV1 of the German Bundespost.

In the main, two tests are carried out on a fully filled cable after manufacture:

The wrap test provides information on the effect of the petro-jelly on the core insulation. In this test, a cable section, approx. 30 cm in length, is kept at 70° C for 7 days. 10 insulated wires are then removed as specimens and each is wrapped round a core of its own diameter to form a close helix of 10 turns. The specimens are then kept at 70° C for 24 hours. The wrap test shall be considered to have been withstood, if in at least 9 of the 10 specimens no cracks in the cooled core insulation are visible with the naked eye.

The waterproof test is the second important one for assessing the quality of the petro-jelly filling. Approx. 1.3 m is cut from the cable under test and subjected to 2 bends in either direction around a bending disc with a diameter 15 times that of the cable. The cable specimen is then straightened and a piece, 1 m in length, removed. One cable end is connected by means of a water hose to a water tank so that the full cross section of the cable end is subjected to a 100 cm water column. The test shall be considered to have been withstood, if no water escapes within 7 days at the end of the vertical test specimen.

In order to register any escape of water, the end of the specimen rests on a strip of paper which is placed between two electrodes. Recording voltmeters automatically register the decrease in the voltage applied at the electrodes, when the paper strip becomes moist as a result of the escape of water.

Cables manufactured according to the new filling method are sure to withstand both tests. Measurements on specimen lengths have shown that on an average the water enters the cable for 10 to 30 cm.

Standard cables

Experience gained to date with the filling equipment, which has been in operation for several years, has been mainly with cables with a low number of pairs (up to 100 pairs) for the distribution network of the German Bundespost.

These cables have the following construction:

The cores consist of a copper conductor, 0.4 mm diameter, insulated with coloured polyethylene. 4 cores form a star quad. In accordance with the German specification VDE 0816 they are marked with black rings for identification. 5 quads in red, yellow, white, green and grey are stranded into a basic unit.

According to the number of pairs required, the cable is constructed from basic units which are also bunched together to form bigger units. 2 impregnated paper tapes are applied longitudinally over the cable core. A bonded copolymer aluminium sheath and an outer PE jacket are applied.

Test cables

In addition to standard cables, test cables up to 200 pairs have also been manufactured according to the new filling method. For special purposes, cables with a low number of pairs with star quads, from 0.8 mm to 1.4 mm copper conductor, have been filled. They are planned for FDM transmission. In all cases, polyethylene has been used as core insulation.

Transmission properties

Mutual capacitance

The filling of the interstices in the cable core with petro-jelly causes an increase in the mutual capacitance of approx. 10 to 20 % owing to the higher dielectric constant of the petro-jelly of 2.2 to 2.3 compared with air. In order to match the mutual capacitance of the filled cable with that of the unfilled cable the wall thickness of the core insulation for filled cables is about 20 % thicker than that for unfilled cables. This means that filled cables have a larger cable diameter.

Figure 3 shows the distribution curve of the mutual capacitance of filled and unfilled cables with 0.4 mm copper conductor with a different number of pairs but the same mutual capacitance. The standard deviation is less in filled cables than in unfilled cables. The graphs for the different numbers of pairs are closer together in filled cables. The petro-jelly filling of the cables has less effect on the variation of the mutual capacitance with the number of pairs in a cable. This does not apply to unfilled cables. As is well known, cables with few pairs have a smaller mutual capacitance than cables with many pairs owing to the higher proportion of air in the cable.

Dissipation factor

The quality of the petro-jelly has an essential influence on the dissipation factor of filled cables. Petro-jelly should not, therefore, contain any moisture. Furthermore, the paper core wrapping can also affect the dissipation factor to a greater extent, if the cable has only a few pairs.

The moisture required for the application of the papers cannot be removed by drying after the manufacturing process, as in the case of paper-insulated cables. In order to keep the influence of the paper moisture on the dissipation factor at a minimum, impregnated paper is used for the core wrapping. In the case of stranded bundled cables, the influence of the core wrapping on the dissipation factor is, however, less than in layered stranded cables.

Although the dissipation factor for the low-frequency range distribution networks with filled cables is only of minor importance, greater significance can arise during later use of the cables for picturephone or PCM at higher frequencies.

Figure 4 shows the curve of the dissipation factor in the range from 1 kHz to 1 MHz. According to figure 4 the dissipation factor drops in the range up to 100 kHz and then rises again. FDM transmission up to a few hundred kHz is therefore not impaired by the dissipation factor.

Insulation resistance

In the measurement of the insulation resistance of petro-jelly filled cables an effect arises which can be traced back to secondary effects in the insulation materials. The insulation resistance in filled cables is considerably lower than in unfilled cables. It increases with time. Figure 5 shows this time function of the insulation resistance.

The relatively low initial insulation resistance of petro-jelly in connection with the good insulating polyethylene can be explained as follows: when direct current is applied in the petro-jelly electrical charges migrate to the limit layers as long as no moving charges exist. These processes are relatively slow. The charge carriers (ions) are formed, as in many other cases, by contamination. After some hours filled cables reach the high insulation resistance of unfilled cables, if high-grade petro-jelly is used.

Cross-talk

The filling of the cables makes the dielectric more homogeneous so that there is no adverse effect on the capacitance unbalance. This is true of both the low-frequency range and carrier-frequency range up to about 500 kHz. Measurements on filled cables which are intended for FDM revealed cross-talk values comparable with those of unfilled FDM cables.

Figure 6 shows the distribution of the capacitance unbalance at 800 Hz, evaluated from a great number of cables.

Uses for filled cables

Filled cables are being used to an increasing extent in the telecommunication network of the German Bundespost. Buried distribution cables with a low number of pairs, which represent the final link with the subscriber are particularly liable to damage and thus to the possible ingress of water. Gas pressure monitoring of these cables is uneconomical. The filling of the cables is the most economic solution with regard to repair costs. The main cables leading from the exchange to the cable distributor and the local cables lying between the exchanges usually still have a gas pressure monitoring system in the German Bundespost network, but the use of filled cables might be possible here too.

Another field of use for filled cables is, for instance, the remote control of equipment in public utilities, railway companies and pipelines as well as pilot cables in adit drainage, whereby the cables must have an extra high standard of reliability.

Future prospects

Cables with a low number of pairs for distribution networks can be successfully filled according to the described method. The following questions arise in regard to further development:

1. Increase of the manufacturing rate.
2. Filling of cables with a higher number of pairs and bigger diameter.

To these questions there are the following possible solutions:

1. Increase in the diameter and especially in the length of the pressure tube and the length of the discharge tube.
2. Pre-heating of the cable core to be filled.

The increase in the length of the equipment is often subject to limitation owing to lack of available space.

The pre-heating of the cable core before entering the filling equipment can be achieved by means of special equipment. During the pre-heating the insulation must not suffer any heat shock, i.e., the temperature of the heat transmitter must not exceed 75° C. Heating with suitably tempered hot air is uneconomical owing to the low heat capacity of air. It is therefore planned to spray liquid petro-jelly onto the cable core. Adequate pre-heating of the cable core is thus achieved in a continuous process. We believe that we can extend the palette of cables filled with petro-jelly by means of this pre-heating equipment.

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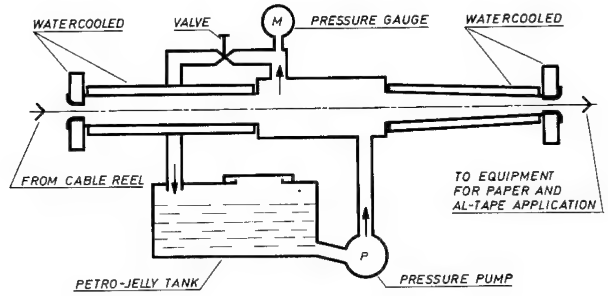

FIG. 1 PRESSURE FILLING METHOD

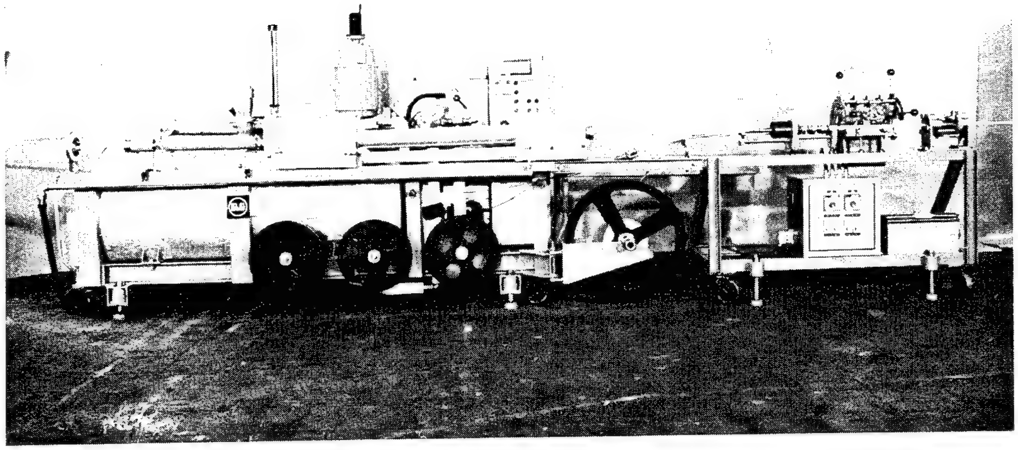

FIG. 2 SIDE VIEW OF THE EQUIPMENT

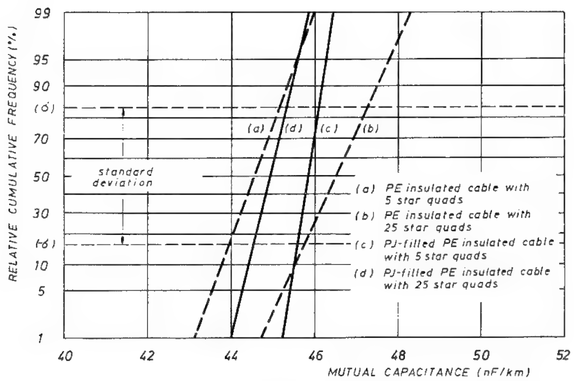

FIG. 3 CUMULATIVE FREQUENCY OF MUTUAL CAPACITANCE
PJ-filled PE insulated cables (0,4 mm) compared with unfilled cables

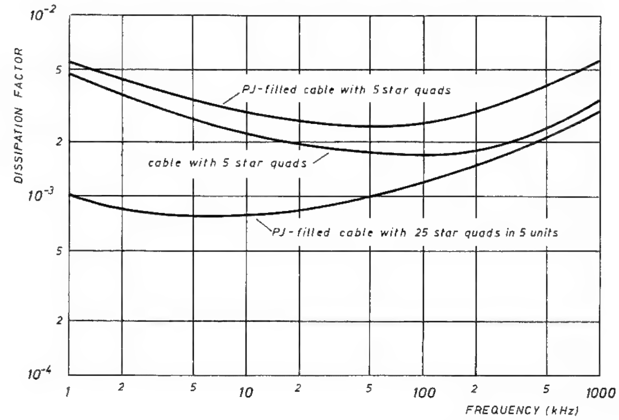

FIG. 4 DISSIPATION FACTOR (0,4 mm PE insulated star quad cable)

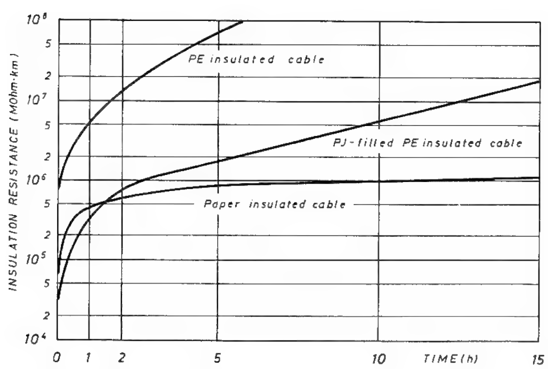

FIG. 5 INSULATION RESISTANCE

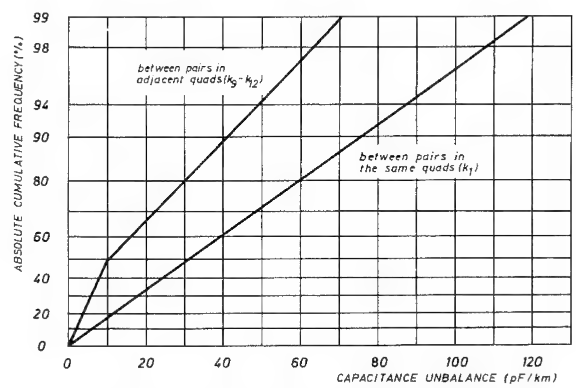

FIG. 6 CUMULATIVE FREQUENCY OF CAPACITANCE UNBALANCE
0,4 mm PJ-filled cable with star quads

A New Method of Manufacturing Laminated Aluminum Polyethylene Sheath Cable

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Summary

A new manufacturing process has been developed for laminated aluminum polyethylene sheath, giving improved moisture proofing properties and better mechanical properties than the conventional one in which aluminum tape coated on one side is used.

In this new manufacturing process, an aluminum tape and an ethylene-copolymer film are bonded together tightly in the sheathing line connected to the extruder in a tandem manner, and then this laminated aluminum tape is longitudinally applied to a running cable core, on which polyethylene is finally extruded as a jacket.

The manufacturing process of laminated aluminum polyethylene sheath is, therefore, completed in a single line operation.

1. Introduction

According to the growth of the petroleum chemicals industry, many kinds of plastics have been developed, and these have brought many changes and advantages to our life. Plastics (especially polyethylene and polyvinylchloride compounds) were introduced for electrical wires and cables as insulation and jacketing a number of years ago.

So polyethylene sheaths have been widely used for various kinds of telecommunication cable, and they contribute to the high reliability of communication systems.

Recently, since cable jackets having stronger mechanical properties, better moisture proofing properties, and so on, were required, laminated aluminum polyethylene sheath was developed and put into practical use because polyethylene sheath alone can not meet the above requirements.

Polyethylene with good mechanical properties is usually used for the cable jacket, but it can not prevent the permeation of moisture and gases. On the other hand, metal tape used as electromagnetic shielding for the cable does not have adequate mechanical strength, particularly when the cable is drawn repeatedly over zigzag routes. These weak-points can be improved by applying laminated aluminum polyethylene (LAP) sheath to the cable.

LAP sheath has been shown to have the following excellent properties.[1)]

1. Superior moisture barrier.
2. Improved mechanical properties.
3. Reduced sheath shrinkback.
4. Improved gaseous barrier.

This type of cable sheath was first developed in England[2)] to improve moisture permeation of a plastic sheath. In the United States of America,[1)] it is also being used on account of the above-mentioned advantages. The realization of these advantages in a finished cable depends upon tight adhesion between the polyethylene sheath and the metal tape.

In Japan, laminated aluminum polyethylene sheath has been introduced by NTT (Nippon Telegraph and Telephone Public Corporation) to solve such problems in color coded polyethylene insulated (CCP) cable as shrinkback of the polyethylene sheath and damage to the aluminum shield of aerial cable, meanwhile this sheath has been used as a moisture barrier in the U.K. and the U.S. With regard to CCP cable, the following problems have been observed[3)].

1. Due to the shrinkback of polyethylene sheath of non-self supporting type cable, the cable core is pushed out of its sheath and protrudes into the ready-access type terminal box after installation, or the cut end of the sheath is pulled from the clamping metal at the splice point.

2. The aluminum shield is damaged during the installation operation when cable is

drawn at unduly sharp traction angles or with excess tension.

In order to improve such defects various studies of their causes and appropriate counter-measures have been undertaken. As a result, it has been concluded that LAP sheath can solve such problems. This LAP sheath cable is now undergoing commercial tests at NTT.

In an ordinary LAP sheath line, an aluminum tape with a thin ethylene-copolymer film which is manufactured by a plastic coating machine is usually applied longitudinally over the cable core before the jacketing process and polyethylene covering is extruded onto it. This manufacturing method has the following defects:

1. It is difficult to slit the laminated aluminum tape in specified widths because the aluminum tape is already annealed and coated with the copolymer film.

2. Splicing of the laminated aluminum tape can not be carried out without interruption or slowing down of the extrusion process because the complication introduced by the coated film interferes with the automated splicing procedure developed for conventional cable.

To solve these problems, we developed the new method of manufacturing laminated aluminum polyethylene sheath cable where the lamination of the aluminum tape and jacketing is completed in single line operation. The new method has the following merits:

1. Splicing of aluminum tape can be easily made by a spot welder, a seam welder, etc. without stopping the extrusion process because aluminum tape and ethylene-copolymer film are separately paid off. An ethylene-copolymer film can be also connected easily. The length of the tape does not put any length limitations on the cable.

2. Laminated aluminum tape made by this method will be less expensive in labor and equipment costs than conventional tapes.

3. Easier slitting of aluminum tape: As the aluminum tape and ethylene-copolymer film are separately prepared, the slitting of the aluminum tape can be done before the aluminum annealing, which will result in easier, better and speedier slitting with less slitting loss and more scrap value.

This paper describes the newly developed method of manufacturing laminated aluminum polyethylene sheath and its characteristics.

2. LAP Sheath using This Method

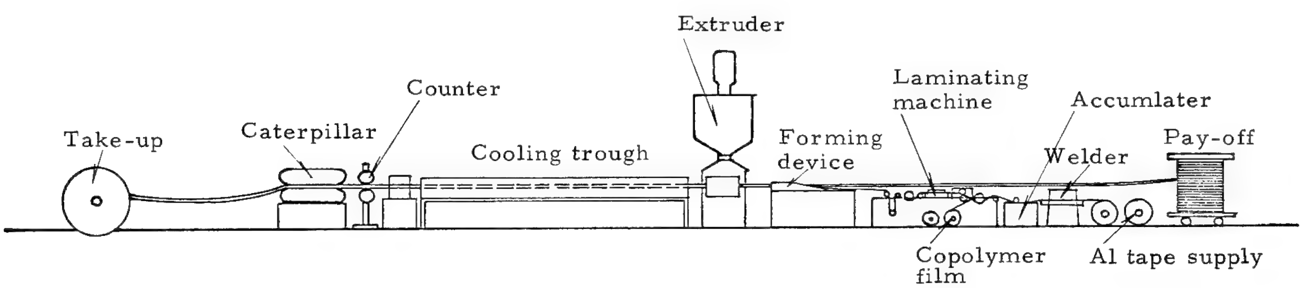
Various types of LAP sheath structure have been considered according to the laminated aluminum tape, such as one side or both side coated, flat or corrugated aluminum, and so on.

Since CCP cable is mostly used aerially in Japan, good shielding characteristics and improved mechanical properties are required of the cable sheath. So, 0.2 mm thick aluminum tape has been adopted in order to obtain about the same electrical resistance as that of conventional lead sheathing. As corrosion resistance is not severely required in aerial cable, one side laminated aluminum tape is used. The flat LAP sheath is used in Japan because of its more effective mechanical properties and lower cost than corrugated types.

Laminated aluminum tape from this method is different in shape from one which is commercially made at present by a coating machine.

A copolymer film which is wider than the aluminum tape is laminated to the tape, and the wider parts of the film are folded back and bonded to the uncoated surface of the aluminum tape. So, both sides of the aluminum tape are fringed with copolymer film.

Fig. 1 New manufacturing line



2.1 Raw materials

In manufacturing the new LAP sheath, the choice of aluminum tape and copolymer film as raw materials is important since the raw materials directly affect the properties of the LAP sheath.

The aluminum tape must be fully annealed and be free from oil stains or other dirt in order to obtain uniform peel strength and good mechanical properties. The aluminum tape is purchased in a thickness of 0.200 mm with a tolerance of ± 0.010 mm.

The adhesive film consists of a double layer film of an ionomer and an ethylene-vinylacetate copolymer, or monolayer film of an ethylene-acrylic acid copolymer. The copolymer film is purchased in a thickness of 0.050 mm with a tolerance of 0.005 mm.

2.2 Tandem sheathing line for LAP sheath cable

As shown in Fig. 1, the equipment is arranged in a tandem manner to the extruder with raw material (an aluminum tape and a copolymer film for adhesion) fed automatically into the line.

The aluminum strip is fed from a dual supply stand into an accumulator. The accumulator permits continuous line operation during coil change where the ends of the aluminum strips are welded together.

In the next stage, as shown in Fig. 1, the copolymer film for adhesion is fed from the dual-supply stand through a heat-seal splicer used for film changing and into an accumulator. It is pulled by line tension. The exit tension is regulated by a specially designed brake, because the film has a low tensile strength. Laminating is accomplished by feeding the aluminum strip, heated by the roller which is set at a constant temperature, and copolymer film through a pair of laminating rollers which apply pressure to cause the bonding. The width of the copolymer film laminated on the aluminum tape is larger by 7 to 10 mm on each side than that of the aluminum tape and these 7 to 10 mm parts are folded back and bonded to the aluminum tape by a specially designed nozzle, to cover both edges of the aluminum tape, so that the both sides of the aluminum tape are fringed with copolymer film.

Then, this laminated aluminum tape is longitudinally applied to a running cable core through a tube forming machine and polyethylene compound is extruded on it.

The fringed edge mentioned above makes it easy to bond the edges of laminated aluminum tape with extruded polyethylene by applying heat and pressure.

Thus, the manufacturing process of the laminated aluminum polyethylene sheath is completed in a single line operation. The following two figures show the structure of the laminated aluminum tape and cable from this manufacturing method.

Fig. 2 Structure of laminated tape

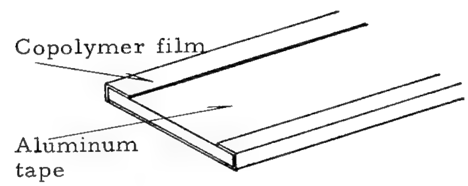
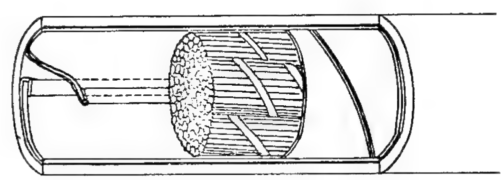


Fig. 3 Cable structure

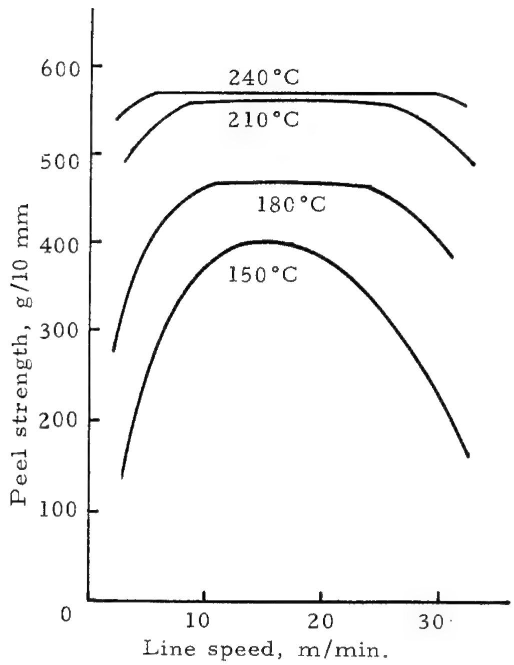


2.3 Peel strength of the laminated aluminum tape

In this new manufacturing method, the peel strength between an aluminum tape and a copolymer film depends upon the temperature of the heater and the line speed of sheathing. Fig. 4 shows the relation-ship between the temperature of the heater, the line speed of sheathing, and the peel strength of laminated aluminum tape.

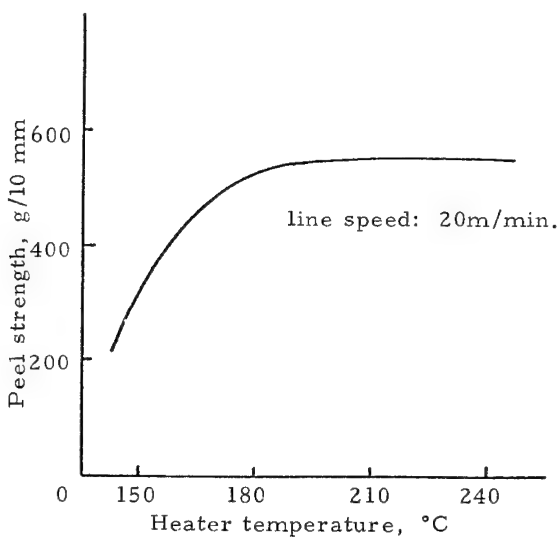
As shown in Fig. 4, the higher the temperature of aluminum tape, the greater is the peel strength of laminated aluminum tape obtained. However, the temperature of an aluminum tape can not be made very high because degradation of the copolymer film might occur.

Fig. 4 Peel strength and line speed



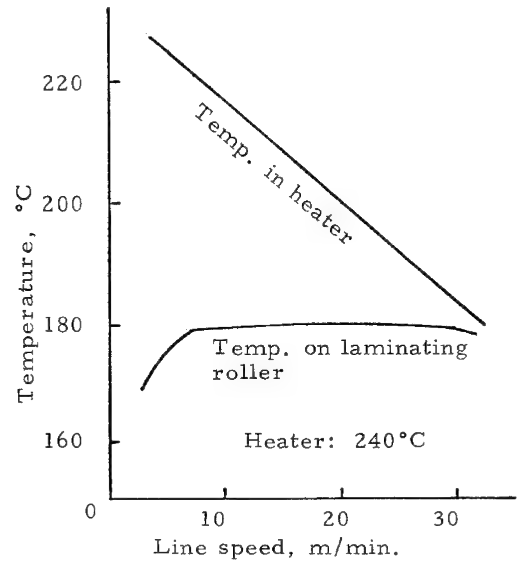
The relation between peel strength and temperature of an aluminum tape is presented in Fig. 5 at a line speed of 20 m/min. A stable and acceptable peel strength is obtained when the temperature of the heater is higher than 180 degree centigrade.

Fig. 5 Peel strength and heater temperature



The temperature of the aluminum tape in the heater decreases linearly with the increase in line speed, when the heater is set at a constant temperature. However, the temperature of the aluminum tape on laminating rollers is almost constant over a wide range of line speed as shown in Fig. 6.

Fig. 6 Temperature of aluminum and line speed



As detailed above, it is important to control the temperature of the aluminum tape and the line speed in order to bond the aluminum tape with a copolymer film tightly. It is also important to control the tension of the aluminum tape and the copolymer film in order to obtain stable peel strength, because vibrations of the tape cause temperature changes of the tape and vibrations of the film make the film wrinkled.

A 180 degree peel test is used for testing the peel strength.

3. Properties of LAP Sheath from this Method

3.1 Moisture proofing

As is well known, LAP sheath has been adopted in England and other countries to improve the moisture proofing of plastic sheathing.

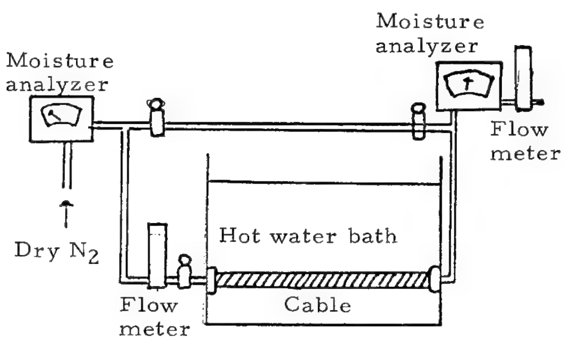
For moisture proofing, the moisture permeation coefficient of various plastic sheathings has been evaluated. LAP sheath made by using

single-side laminated aluminum tape has a moisture permeation coefficient of about 1/50 that of conventional alpeth sheath. A moisture permeation coefficient as small as 1/3000 that of alpeth sheath can be attained, when an aluminum tape laminated with copolymer on both sides is used as shielding for LAP sheath.

LAP sheath using this new manufacturing process has the same moisture permeation coefficient as that of both sides laminated aluminum tape.

The moisture permeability is measured by a Moisture Analyzer. The block diagram of moisture permeability measurement apparatus is presented in Fig. 7

Fig. 7 Block diagram of moisture permeability measurement apparatus



Organic solvent permeability is also studied the results show that LAP sheath from this new method has an organic solvent (xylene) permeation coefficient approximately 1/1000 that of polyethylene sheath and 1/100 that of LAP sheath using one side laminated aluminum tape. Based on this fact, it can be concluded that this LAP sheath cable is suitable for use as an organic solvent barrier in chemical engineering plant, etc. [4]

3.2 Mechanical properties

Besides good moisture proofing, LAP sheath has been used by NTT because it provides excellent mechanical properties in comparison with alpeth sheath. The superior mechanical properties of this LAP sheath make the installation operation easier and reduce the damage to cable by typhoons, and so on. However, LAP sheath cable has less flexibility than alpeth sheathed cable, and tends to be damaged inside the polyethylene jacket when the overlapped part of an aluminum tape is struck at low temperature.

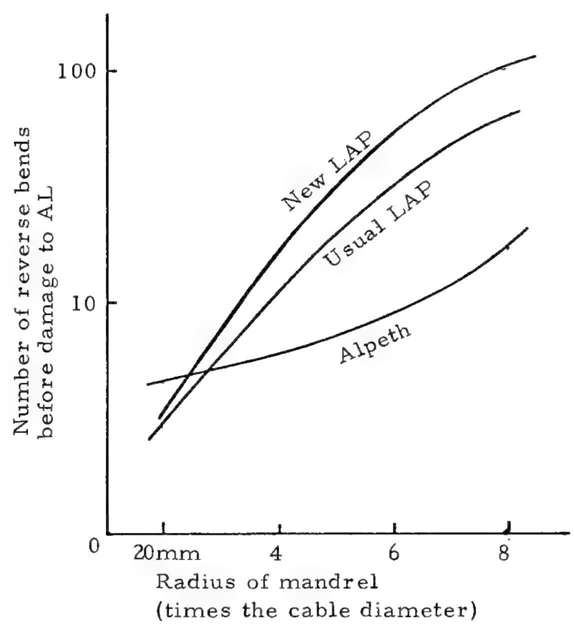
LAP sheathing from this new process posseses betters mechanical properties than conventional one side coated aluminum tapes as follows:

1. Better reverse bending properties.
2. Superior shock load characteristics at low temperature.

These are due to the tight bond of the overlaped of the aluminum tape.

The reverse bending properties of new LAP sheath, conventional LAP sheath, and alpeth sheath are shown in Fig. 8.

Fig. 8 Reverse bending properties (0.4 mm 200p)



In testing bending characteristics, a cable sample shall be bent in reverse over a mandrel with a radius of 20 mm, and 4, 6, 8 times the actual diameter of cable. Fig. 8 shows the number of reverse bendings before the aluminum shield cracks.

The shock load characteristics of new LAP sheath and a conventional one at low temperature are listed in Table 1.

Table 1 - Shock Load Test at Low Temp.

Temp. °C	-20	-25	-30	-40
New LAP	0/20	0/20	0/20	0/20
Usual LAP	0/20	2/20	5/20	9/20

Number of Failures/number of samples

The shock load property at low temperature shall be checked by the following test. The overlapped portion of the specimens is struck with a 0.45 kg iron ball dropped from a height of 0.9 meters at each temperature.

4. Splicing of Aluminum Tapes

4.1 Method of splicing

In cable manufacture, aluminum tape for shielding must be spliced as supply coils run out. The splicing must be made in the smallest time possible to avoid interruption or slow down of the extrusion process. When a coated aluminum tape is used, the complications introduced by the plastic coating interfere with the splicing procedure developed for conventional cable.

In this new manufacturing method, splicing of aluminum tape can be easily made by conventional welding procedures such as seam welding, ultrasonic welding, and so on without stopping or slowing down the extrusion process, because aluminum tape and copolymer film are individually paid off.

Laboratory investigations and field tests were carried out to determine suitable splicing procedures. Various splicing methods such as cold welding, spot welding, seam welding, ultrasonic welding, etc. were tested by a bending test, 180° peel test, shock load test at low temperature, and aerial installation operation.

From these results, it has been concluded that cold welding and spot welding do not comply with the requirements for mechanical properties and moisture proofing. Enough mechanical strength and moisture permeability in the splicing part can be obtained by seam welding or ultrasonic welding, when the spliced part is introduced into the new LAP sheath.

4.2 Properties of the joint

The joint resistance of the aluminum tape by seam welding was the same as that of the aluminum tape itself. The resistance of the aluminum tape is about 3×10^{-6} ohms/cm.

Tensile strength and elongation (at break) of the joint part was also measured. Results are listed in Table 2.

Table 2 - Tensile Properties of Aluminum Tape

	Tensile strength at break (kg/mm^2)	Elongation at break (%)
Jointed part	7.2	14
Regular part	7.6	25

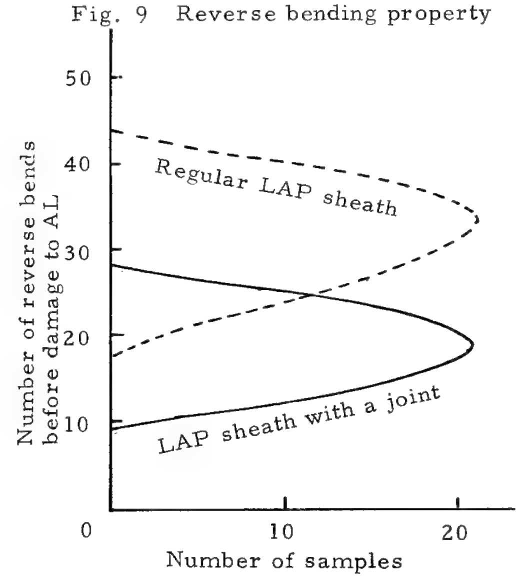
The moisture permeation coefficient of LAP sheath with jointed aluminum tape is equal to that of regular LAP sheath using this method. As the joint of the aluminum tape is seam-welded, so moisture can not pass through the joint.

Fig. 9 shows the number of reverse bendings of regular LAP sheath and LAP sheath with a tape joint before the aluminum shield cracks.

LAP sheath with an aluminum joint has about 1/3 less the number of reverse bendings than regular LAP sheath has. This value is, however, acceptable for the mechanical properties of LAP sheath.

Other properties of LAP sheath with a joint are almost same as the regular one.

Fig. 9 Reverse bending property



Conclusion

A new manufacturing process of laminated aluminum polyethylene sheath cable has been developed, which surpasses the conventional one in various technical and economic respects.

In this new LAP sheath line, aluminum tape and copolymer film are separately paid off and laminated tightly together in the sheathing line. So this method contributes to a reduction of cost and an improvement of various properties. Especially, the splicing of an aluminum tape and a copolymer film can be easily made without stopping or slowing down the process which raises productivity markedly, resulting in a reduction of the cable manufacturing cost.

Acknowledgement

The authors wish to thank the people at NTT for their guidance and our associate who contributed to the development of this method.

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FOAM-SKIN, A COMPOSITE EXPANDED INSULATION FOR USE IN TELEPHONE CABLES

by

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ABSTRACT

This new composite insulation makes it possible to produce waterproof telephone cables of approximately the same size, and with the same basic properties, as the unfilled cable. The paper describes methods of design, manufacture and choice of polymers, together with results of life studies on the insulation systems.

INTRODUCTION

The waterproofing of plastic insulated (PIC) paired telephone cables by filling the interstices of the cable core with a water resistant compound has been accepted as a solution to problems caused by water entering the cables. Initial development for the fully filled cable made use of conductors insulated with solid polyolefins and these cables met all the requirements for a waterproof cable. However, because of the greater dielectric constant (SIC) of the filling compound compared to that of air, it is necessary to increase the overall diameter of the insulated conductor, and so that of the completed cable, to keep the mutual capacitances of the unfilled and the filled cable the same.

To reduce these cable dimensions, and thus the cable cost, air must be reintroduced into the cable core, and the logical way to do this is to use a cellular dielectric. From the start of the development, the objective was to produce a more economical waterproof cable which would be capable of meeting all the present filled PIC requirements, including those for dielectric strength. The new cable would also be as robust and have a service life equivalent to that of regular PIC cables. The construction chosen to fulfill these requirements was foam-skin - a composite insulation consisting of an inner layer of natural foam covered by a coloured skin of solid insulation. This insulation system was compared to regular PIC, filled PIC with solid insulation and filled PIC with an expanded dielectric.

WHY THE COMPOSITE INSULATION?

It was believed at the start of the development programme that the composite insulation in filled cable would have the following advantages.

Improved Resistance to Ageing

It has been shown by other investigators[1,2] that insulation pigments in contact with copper conductors shorten the life of polyolefins. The composite has all the pigment in the outer skin of the insulation, and the system should have a longer life.

Reduced Size

It was found from laboratory investigation that the breakdown voltage of the insulation between wires is dependent upon the average percentage of air in the insulation, providing a closed cell structure is maintained. The breakdown voltage is substantially independent of the distribution of air through the dielectric. This holds true at least for the ranges of insulation thickness and percentage air content considered.

The distribution of the air in the dielectric is of great importance when considering capacitance. For a given overall diameter and average insulation density, the capacitance will be lower when the air is closer to the conductor than when the air is uniformly distributed throughout the insulation.

This effect is shown in Fig. 1 for 22 AWG insulated conductors suitable for use in completed cable with 0.083 μF/mile mutual capacitance. For the same dielectric strength and for any percentage air content the overall diameter of a foam insulation will be larger than the foam-skin insulation.

The Skin As A Barrier

It has been shown[4] that the filling compound is absorbed by the foam insulation. The solid skin should reduce this affect.

A further advantage is that, by using a dual insulation, there will be a lower probability of coincident pinhole faults. This should result in greater uniformity and reliability of dielectric strength over that for an insulation applied by a single extrusion.

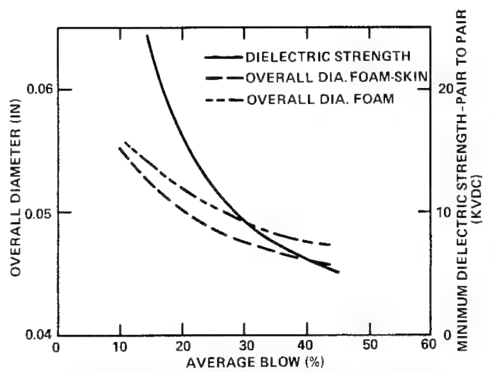


FIG. 1 DIMENSIONS & BREAKDOWN VOLTAGE OF 22AWG INSULATED CONDUCTORS SUITABLE FOR 0.083μF/MILE CABLE

MANUFACTURE

To date, approximately 1000 miles of cable with both copper and aluminum conductors in the range 19 AWG to 24 AWG have been made in sizes up to 300 pairs. These cables have a nominal mutual capacitance of 0.083 μF/mile. The design either has been standardised or is being given field trials by four operating companies.

The conductor is insulated with an inner layer of natural foam polypropylene, with an air content ("blow") of 30-40% and this is covered with a skin of from 2-5 mils of solid coloured, medium density polyethylene (MDPE). The insulated conductors are twisted and stranded as for regular PIC cables. The cable cores are filled with a suitable filling compound and jacketed using a longitudinally applied two side coated aluminum tape bonded to an overall MDPE jacket.

A more detailed description of the special techniques used to produce the foam-skin insulated filled cable is given below.

Insulating

The foam-skin insulated conductors are manufactured on standard high speed extrusion lines to which have been added second extruders working in tandem with the primary extruders. In addition, more sophisticated temperature controls are utilized together with facilities for the continuous monitoring of capacitance, diameter and pressure. The main features of the foam-skin extrusion lines are given in Table 1.

TABLE 1 EXTRUSION LINE

MAIN EXTRUDER:	2-½", 24:1 L/D RATIO
MAIN EXTRUDER SCREW:	10 TURN METERING, 3:1 COMPRESSION RATIO
SECONDARY EXTRUDER:	2-½", 20:1 L/D RATIO
CROSS HEAD:	LOW INVENTORY CARTRIDGE TYPE
DIAMETER MONITOR:	CONTACT TYPE WITH INDICATOR & RECORDER
CAPACITANCE MONITOR:	TROUGH MOUNTED - ONE (1) FOOT ELECTRODE RANGE 0 - 100 pf/ft
PRESSURE MONITOR:	PNEUMATIC TRANSMITTER WITH INDICATOR RANGE 0 - 10,000 psi
TEMPERATURE CONTROLLERS:	THREE (3) MODE SOLID STATE WITH RECORDERS

Fixed centre tooling is used, the design of which is made relatively simple in order to avoid unduly long set-up time on the production lines. The die holder (cartridge) is made in two sections. The first section contains the core tube (tip) and the die which forms the primary insulation around the copper conductor. This portion is completely enclosed in the crosshead. The second section contains the die which forms the "skin" around the primary insulation. This section is external to the crosshead, and is fed by the second extruder as can be seen in Fig. 2.

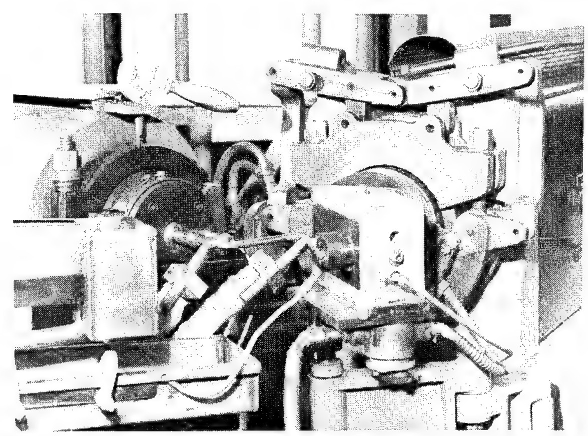


FIG. 2 DUAL EXTRUSION COMPLEX

It was found that standard polyethylene dies were unsatisfactory for the production of concentric cellular insulation with the polymers being used, so a special non-landed die was designed to overcome this problem. The core tube (tip) and skin applicator die are the same design as used for solid polyethylene extrusion.

Compound Processability

The initial runs of foam-skin insulated conductor were made using low flow rate ethylene-propylene copolymers with a blowing agent of the Azodicarbonamide type. It was soon realized that these materials were unsuitable in their expanded form due to poor cell structure (Fig. 4) and lower than anticipated dielectric strength.

Properties listed in raw material specifications available for polypropylene might be relevant to actual performance once the polymer is on the finished product, but are quite meaningless when used for selecting materials with respect to processability. The problem is further aggravated if the product in question involves a cellular structure. A study was undertaken aimed at defining the molecular and/or rheological parameters which are relevant for processability and cell formation. A number of properties tested on different batches of the same type of material were ranked in the order of processing performance in production.

The most important parameters for our type of operation were found to be high flow rate accompanied with a high degree of viscoelasticity, a minimum viscosity value at 300 sec^{-1} shear rate, fast crystallization rate, high activation energy corresponding to the β relaxation process and slow frequency response of the storage modulus in the terminal region. The values listed in Table 2 are typical of base resins with satisfactory processing characteristics. The product manufactured with these parameters gave uniform cell structure, improved processability and excellent dielectric strength - Fig. 5.

TABLE 2 BASE RESIN PROPERTIES

FLOW RATE AT 230°C		g/10 MIN	MIN 1.5
DIE SWELL		%	MIN 25
VISCOSITY AT 190°C	a)	p x 10^3	MIN 5.5
CRYSTALLIZATION TIME AT 127°C	b)	SECS	MAX 100-200
ACTIVATION ENERGY	c)	Kcal/mol	MIN 30
LIMITING LOGARITHMIC SLOPE (G')	d)	----	MAX 1.6

NOTE:
a) INSTRON CAPILLARY RHEOMETER, DIE L = 0.1 IN., D = 0.02 IN.
b) DSC, ANNEALING AT 200°C
c) β RELAXATION IN THE DYNAMIC MECHANICAL SPECTRA, SINGLE RELAXATION TIME MODEL
d) G' = STORAGE MODULUS DYNE/CM^2 MEASURED ON ORTHOGONAL RHEOMETER

The listed values, however, are subject to the blowing agent concentration. In Fig. 3, viscosity curves are shown for two blowing agent concentrations in comparison to that of the base polymer. Increasing blowing agent concentration results in lower melt viscosity, permitting lower extrusion temperatures for a given degree of blow.

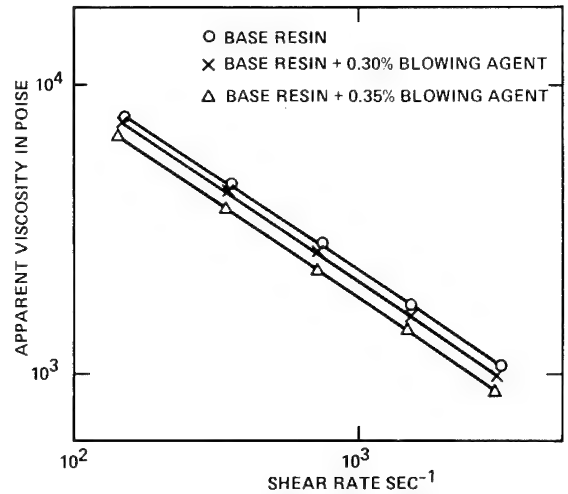


FIG. 3 EFFECT OF BLOWING AGENT CONCENTRATION ON VISCOSITY

Extrusion Line Stability

Operation of the extrusion line is found to be dependent on the following:

a) Stability of barrel temperature controllers to within ± 1/4°F of the set point. This is particularly critical in the forward zone of the metering section.

b) Similar accuracy is required in the control of line speed, extruder RPM as well as preheat and annealing temperatures.

c) Tight control over the quantity of blowing agent in the base polymer. A 5% variability from batch to batch is considered to be satisfactory.

Given this stability, it was found that capacitance can be controlled to within ± 1/2 pf/ft and the diameter to within ± 0.0005" of the nominal values when running at PIC line speeds.

Comparison of Foam & Foam-Skin Extrusion Processes

While foam and foam-skin extrusion processes have much in common, there exist basic differences, which from experience, make the foam-skin operation easier to control and the resultant product superior in quality. The following highlights some of these points:

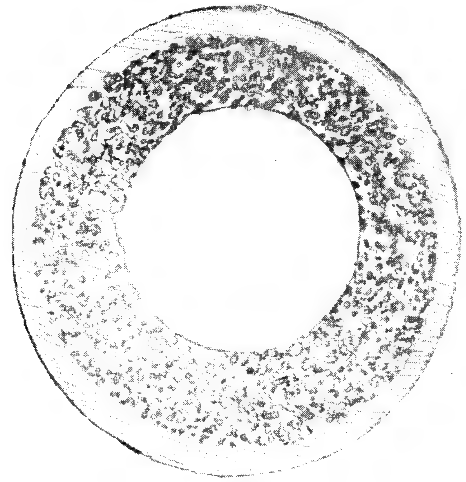
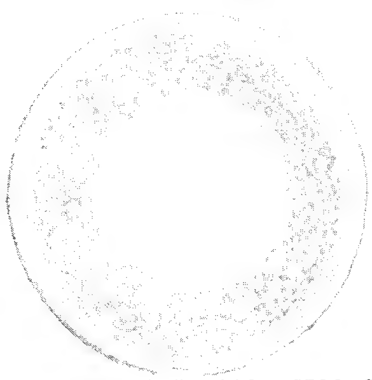


FIG. 4 FOAM-SKIN POOR CELL STRUCTURE



Same Magnification as Fig. 4

FIG. 5 FOAM-SKIN GOOD CELL STRUCTURE

a) Similarities

(i) Similar temperature profiles are used.

(ii) Scrap rates are approximately the same at start-up due to process stabilization.

b) Advantages of Foam-Skin

(i) Little or no change in capacitance caused by the pigment when changing colour on the run.

(ii) Better surface quality of the insulated conductor at high levels of expansion.

(iii) No change in colour regardless of the level of expansion.

(iv) Reduced scrap at colour change.

(v) Superior dielectric strength of singles, e.g. Average breakdown voltage single tested AC in water. Foam - 2.5 kV. Foam-skin - 6.0 kV.

Twisting and Stranding

As stated earlier, foam-skin is processed through these operations in the same manner as regular solid insulations. No special precautions are taken in its handling. Fault levels in core form are substantially lower than those for solid PIC cables.

Filling & Jacketing

The system used at our factory for fully filling foam-skin and solid insulated cables was developed with the intention of filling the completed cable core in one operation. To date, cables as large as 300 prs have been successfully filled in this manner.

The filling compound is a highly refined oil-modified parafin which is stored and processed at approx. 200°F. This material is completely compatible with the product and shows no decomposition or separation during storage or processing.

The first component in the filling system is a pressure vessel fitted with unique, long life, iris type seals which are infinitely adjustable and can accommodate a complete range of cable sizes up to 3-1/2" in diameter - Fig. 6. As the cable core is drawn through this filling tube, the hot compound is pumped into the system and the iris seals adjusted to provide the required pressure in the tube to fully penetrate the core.

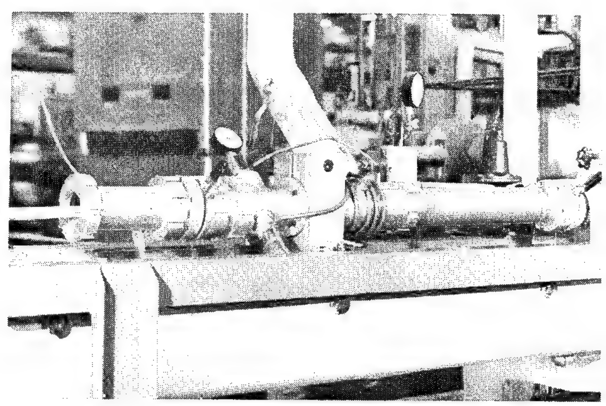


FIG. 6 PRESSURIZED FILLING TUBE

The filled core is then passed through a second applicator where a thin coat of cooler compound is applied to the outside of the cable. This ensures a complete fill of all surface interstices to prevent water leakage between core and core wrap.

A final coating of compound is applied over the core wrap, following which a bonded aluminum sheath is formed snugly around

the filled core. This third coating is intended to eliminate any water leakage between the core wrap and the sealed aluminum sheath.

Inspection Procedures

In Process Inspection of Cell Structure And Wall Thickness. To properly inspect a conductor of the foam-skin construction one must be able to accurately measure the thickness of the skin, the dimensions of the inner expanded dielectric and be able to visually examine the cell structure. This cannot be accomplished with conventional inspection equipment; it requires the use of a microtome and profile projector.

The procedure consists of cutting cross-sectional samples of insulation, .002" to .003" in thickness on the microtome. These samples are mounted on glass slides, placed on the shadowgraph and magnified 50 times. The resultant image is projected on a screen (Fig. 7) from which exact measurements can be taken. Figs. 4 and 5 were made using this method.

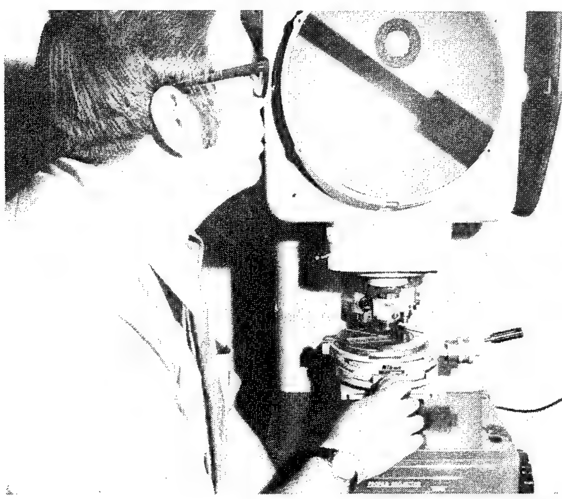


FIG. 7 INSPECTING FOAM-SKIN INSULATION

"In Process" Inspection of Fill. An in process inspection is required to give the operator an indication that he is filling the cable adequately. A one foot vertical sample of cable is subjected to a three-foot head of water. If no leakage is observed after 15 minutes the quality of fill is considered satisfactory to continue running.

Inspection of Finished Cable. Foam-skin cables are tested to the same specifications as filled cables with solid insulation. The data in Table 3 are typical values, and show that they are suitable as substitutes for solid insulation cables. The 19 and 24 AWG cables also pass all the tests, including dielectric strength of 10 KV for 19 AWG cables and 5 KV for 24 AWG cables.

TABLE 3 TYPICAL TEST RESULTS

ELECTRICAL TESTS:	FILLED PIC TYPICAL SPECIFICATION	0.083μF/MILE MUTUAL CAP. 22 AWG FOAM-SKIN (16-200 PAIR)
RMS DEVIATION OF MUTUAL CAPACITANCE	<3%	1.7%
CAPACITANCE UNBALANCE	AV = 30 PICA FARADS/1000'	15
(PAIR TO PAIR)	HIGHEST = 160 PICA FARADS/1000'	125
(PAIR TO SHIELD)	AV = 75 PICA FARADS/1000'	40
	HIGHEST = 300 PICA FARADS/1000'	250
INSULATION RESISTANCE	>1000 MEG OHMS/MILE	10,000 MEG OHMS/MILE
MUTUAL CONDUCTANCE	<2 MICRO MHOS/MILE	0.1 MICRO MHOS/MILE
DIELECTRIC STRENGTH	PAIR TO PAIRS = 8 kV CONDUCTORS TO SHIELD = 15kV	PASSED
NEAR END CROSSTALK @ 150kHz	RMS AVERAGE 72.5dB/4500' 99% BETTER THAN 57.5dB/4500'	84 dB 61 dB
PHYSICAL TESTS:		
TENSILE AFTER	1000 PSI MIN.	2700 PSI
ELONGATION 14 DAYS @ 70°C	200% MIN.	450%
COLD BLEND	-55°C FOR ONE HOUR (3 x O.D.)	NO CRACKS
SHRINKBACK	100°C FOR 24 HOURS <1/8" ON A 6" SAMPLE	PASSED
WATER PERMEATION	<25cc/HR. AT END OF 2ND HOUR	PASSED

The water permeation is measured using the horizontal water test. The jacket shield and core wrap of the centre 6" of a 6-foot length of cable are removed to expose the pairs. A watertight closure is placed over the exposed pairs and secured over the jacket either side. A 3' head of water is applied to the closure and leakage is measured from the ends of the cable (see Fig. 8).

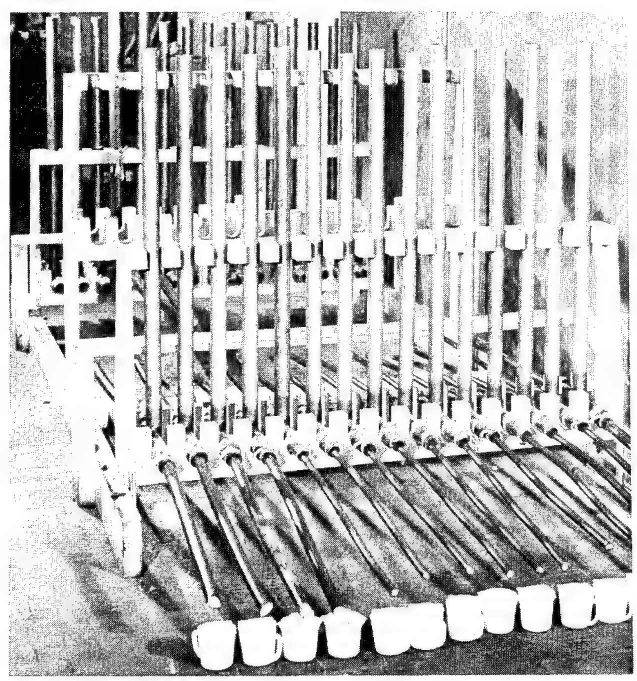


FIG. 8 WATER PERMEATION TESTING APPARATUS

The intent is to have no leakage from the cable after 14 days under the 3' head of water.

Transmission Properties

Values of typical transmission properties of the foam-skin insulated filled cable are shown for 22 AWG conductors in Table 4, and these are compared with the values for standard PIC cables and filled cables with solid insulation. It can be seen that the foam-skin cable has properties which lie between the other two types of cable. At frequencies up to 250 kHz the attenuation of the foam-skin cable is essentially the same as the regular PIC cable while at 772 it is about 9% lower.

Dielectric Strength

Breakdown voltages have been determined between 22 AWG conductors insulated with solid LDPE, foam, or foam-skin. The voltages were measured using a.c., d.c., and an impulse surge. The values are recorded in Table 5 together with surge breakdown voltages between the core and sheath for sealed Alpeth jacket. The surge voltage had a standard 1/40 wave shape and was derived from a small laboratory impulse generator. The foam-skin cable is seen to easily meet all dielectric strength requirements, including the surge testing requirements currently under consideration.

Other Applications for the Foam-Skin Insulation

The foam-skin principle has been applied to other cables. One example is a new system-optimized cable - SUPER-xT(R)- which has been developed specially for PCM (T1) carrier use. Another is in the 59 type coaxial cable with improved shielding recently introduced.

TABLE 5 DIELECTRIC STRENGTH

CONDUCTOR INSULATION	BREAKDOWN VOLTAGE (kV) ON 30 FT. SAMPLES			
	BETWEEN PAIRS			CORE TO SHEATH
	AC	DC	SURGE	SURGE
SOLID	18	38	57	22
FOAM	4½	9	11	14
FOAM-SKIN	12	30	33	25

TESTS FOR ROBUSTNESS OF INSULATION

Both insulated conductors and completed cables were subjected to various tests to satisfy the original requirement of robustness.

Bend Test

Samples of conductor insulated with foam, solid polyethylene and foam-skin were bent around mandrels of from 4 x OD to 1 x OD of the insulated conductor at ambient and at -40C. Also samples which had been bent around a 1 x OD mandrel at ambient were straightened at -40C. None of the insulation types tested cracked at these temperatures.

Short lengths of foam-skin cables were tested by bending samples around mandrels

TABLE 4 TYPICAL TRANSMISSION CHARACTERISTICS -22 AWG COPPER CONDUCTOR

FREQUENCY (kHz)	ATTENUATION (dB/Mile)			PHASE CHANGE (Radians/Mile)			VELOCITY OF PROPOGATION (X 1000 Miles/Sec)			CHARACTERISTIC IMPEDANCE (Ohms)		
	PIC	FILLED PIC	FOAM-SKIN	PIC	FILLED PIC	FOAM-SKIN	PIC	FILLED PIC	FOAM-SKIN	PIC	FILLED PIC	FOAM-SKIN
1	1.8	1.8	1.8	0.2	0.2	0.2	29.7	28.5	29.4	684	570	568
10	5.0	4.8	4.9	0.8	0.8	0.8	79.1	76.6	78.0	189	190	189
48	7.2	6.9	7.1	2.9	3.0	2.9	107	101	104	119	124	120
96	8.5	8.1	8.5	5.3	5.8	5.6	111	104	108	106	118	113
136	9.6	9.1	9.6	7.2	8.1	7.8	113	105	110	105	116	111
168	10.5	9.8	10.4	8.9	10.0	9.5	115	106	111	103	115	110
208	11.4	10.5	11.3	10.9	12.3	11.7	116	106	111	101	114	109
256	12.6	11.7	12.5	13.6	15.1	14.3	116	107	112	100	113	108
772	23.2	19.5	21.0	40.1	44.1	41.8	121	110	116	99	110	104

of 20 x OD and 12 x OD of the cable, and also by bending sharply without a mandrel. It was found that the foam-skin insulation had the same conductor to conductor dielectric strength after bending as before bending. This test shows that even if the insulated conductors are severely bent during installation, the insulation will remain intact around the conductor, and the cables remain serviceable.

Impact Testing

Small weights, 1/4" in diameter, weighing between 20 and 40 gms., were dropped onto insulated conductors at both ambient temperature and at -40C. Impact strength was defined as the force required to just expose the conductor. Except for MDPE foam, which was very easily cut through, the plot of impact strength against wall thickness shown in Fig. 9 was found to be true for solid, foam and foam-skin insulations. At -40C more force is required to cut through the insulation than at ambient. None of the insulation shattered at -40C but flattened as in the ambient test.

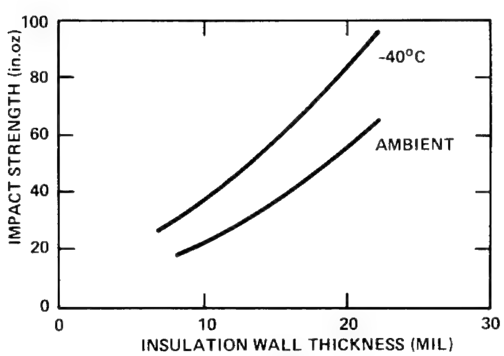


FIG. 9 IMPACT TEST

Compression Testing

Two lengths of insulated conductors were twisted to give ten evenly spaced twists in a length of 4". The middle two inches of the twisted pair was placed between polyethylene coated flat rigid metal plates. The insulation resistance and a.c. breakdown voltage were measured with loads of 0, 11 and 25 lbs applied to the plates.

There was no measurable change in insulation resistance with the different loads. There was, however, a noticeable decrease in the breakdown voltage of solid low density polyethylene (LDPE) insulation, and a slight decrease for foam polypropylene. No change was detected for the foam-skin insulation - Fig. 10.

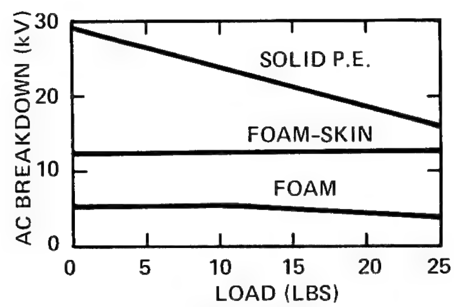


FIG. 10 COMPRESSION TEST

Examination of the samples after testing showed that the solid insulation wall was thinned by the test, whereas the foam insulation acted as a cushion, even though the cells collapsed. The foam-skin had a collapsed cell structure after the test, but the skin thickness was unchanged.

After two months at 70C, foam MDPE in contact with the filling compound was shown to retain only 20% of its original elongation. These aged samples were very soft, and when tested with the 25 lb load, they averaged only 60% retention of their dielectric strength before ageing.

TESTING FOR SATISFACTORY SERVICE LIFE

Thermal Stability

The first part of the study on the stability of insulation was concentrated on the oxidative thermal stability of the polymer in contact with copper and/or filling compounds. Various techniques were employed in evaluating the effectiveness of antioxidant - copper inhibitor systems. Copper "poisoning" was simulated by incorporating 0.5 percent of copper stearate.

Thermal Analysis. Polypropylene samples each with one of four antioxidant - copper inhibitor compositions A, B, C and D, and another sample not containing copper inhibitor, were evaluated on the Perkin Elmer TGS system under isothermal conditions at 210C in an oxygen atmosphere. Typical thermograms are shown in Fig. 11. Times to base line shift - referred to as induction time - were recorded in seconds.

Stabilizer systems C and D offer the best protection against copper induced degradation and are highly superior to A which is an accepted system in wire coating grade resins. Also the LDPE generally

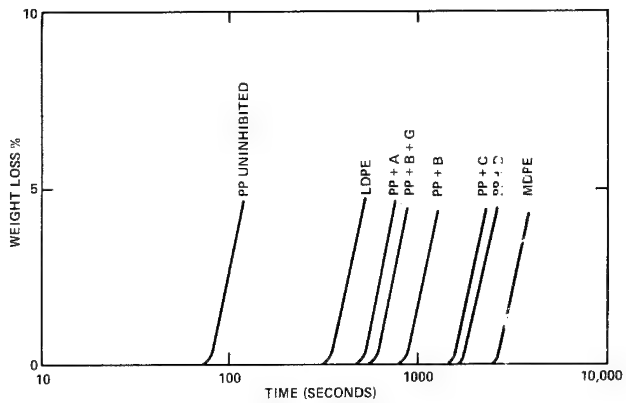


FIG. 11 ISOTHERMAL THERMOGRAMS AT 210°C

used for standard PIC cables in the past exhibited similar thermal stability. The insulating material currently used for the foam-skin structure contains the stabilizer system D. The MDPE has been included for comparison to illustrate its excellent stability. It is not in direct contact with the copper in the foam skin insulation system, therefore, no inhibitor is used in the formulation.

The reduced induction period - from 822 to 610 secs - in the presence of green pigment demonstrates one of the advantages of the foam-skin design, where the inner insulation is unpigmented.

TABLE 6 STABILIZER EFFECTIVENESS-IGA AT 210°C

INSULATION	INDUCTION TIME (SEC)
PP UNHIBITED	84
PP STABILIZER SYSTEM A	576
PP STABILIZER SYSTEM B	822
PP STABILIZER SYSTEM B + GREEN PIGMENT	610
PP STABILIZER SYSTEM C	1788
PP STABILIZER SYSTEM D	1950
MDPE UNINHIBITED	2640

The use of colouring materials with the foamable polymer also creates difficulties in processing. The decomposition reaction of the blowing agent can be accelerated or delayed depending upon the type of pigment used.

A study was made of the effects of the filling compound on three of the above stabilizer systems. The exothermic nature of the degradation was utilized by measuring the time required to induce oxidation under controlled conditions. The test was performed on the Perkin Elmer DSC Model B1. Disks approx. 20 mg. in weight were cut out from compression moulded films. Previous treatment included immersion in a filling medium at 70C for two weeks. Two filling compounds were tested, compound E and a polyethylene grease blended with polybutene (compound F). The test specimens were heated at 10C/min. rate to 200C in a nitrogen atmosphere. The mode was then changed to isothermal and oxygen was introduced at a rate of 30 cc/min. Times to exothermic base line shift - induction time - were recorded in seconds. The results are shown in Table 7.

TABLE 7 OXIDATIVE STABILITY IN DSC

	INDUCTION TIME IN SECONDS STABILIZER SYSTEM		
	A	B	C
VIRGIN NO COPPER	1235	2475	>5000
VIRGIN + COPPER	262	1825	2158
FILLING COMPOUND E NO COPPER	531	1920	2721
FILLING COMPOUND E + COPPER	110	1312	2116
FILLING COMPOUND F NO COPPER	1029	2050	2669
FILLING COMPOUND F + COPPER	242	1426	2451

Stabilizer system C again exhibits the best thermal stability. Both B and C have a higher induction time when in contact with copper and/or exposed to the filling medium than composition A. These data also indicate that compound E is a more powerful environment than the compound F. Although the filling material does reduce the oxidative stability, particularly in the presence of copper, the polypropylene foam of the foam-skin insulation is separated from the filling material by the skin, which is a MDPE and whose excellent performance in these environments was discussed earlier.

Copper/Aluminum Dish Test. Compression moulded strips 30 mils thick were used in rectangular containers formed from copper and aluminum foil. Three sets of samples were prepared:

a) moulded strips of polypropylene containing stabilizer systems B and C.

b) moulded strips of samples as in (a) but

covered (heat sealed) with MDPE strips of the same thickness.

c) moulded strips of samples as in (a) which had been immersed in filling compound E for a period of two weeks at 70C.

Samples were carefully wiped after being removed from the filling compound and the MDPE strip was peeled off prior to flow rate measurements. The results are shown in Table 8. These data again confirm the superior stability of stabilizer system C and also indicate that the MDPE strip offers some protection against oxidation. The flow rate measured on specimens exposed to the filling material is an apparent flow rate due to absorption which reduces the viscosity of the polymer. It should be borne in mind that the reproducibility of the copper/aluminum dish test is quite poor and is applicable for the evaluation of the same type of polymers only (flow rate range).

TABLE 8 COPPER ALUMINUM DISH TEST

STABILIZER SYSTEM	Al	Cu	Al + FILLING COMPOUND	Cu + FILLING	Al + PE	Cu + PE
B	1.47	1.93	2.71	3.50	1.05	1.32
C	1.10	1.06	1.39	1.32	1.15	1.08

FLOW RATE IS MEASURED AT 190°C AND THE CHANGE IS EXPRESSED AS A RATIO

Thermal Ageing In The Presence of Copper. The effect of copper on the stress strain properties was determined on tensile specimens cut from compression moulded slabs containing 0.5 percent of copper stearate (incorporated on a two roll laboratory mill at 350-360F). The test specimens were exposed to 145C for a period of one, three and seven days and a set of samples was immersed in compound E at 70C for two weeks. Tensile strength and elongation were measured and percent retention to blank calculated. Also visual observation was made on discoloration (Table 9).

The physical properties are virtually unaffected by the 70C immersion and the ageing for one day at 145C. The material containing stabilizer system A decomposed after three days and developed a dark brown colour. Stabilizer B disintegrated after seven-day exposure. Both systems C and D withstood the seven-day exposure without becoming brittle and with no discoloration evident. These results are in good agreement with those obtained by thermal analysis.

Foam-Skin Advantages. Based on the foregoing, the advantages of the foam-skin construction with respect to oxidative thermal stability can be summarized as follows:

1. The foamable material is extruded at lower temperatures than the same material in solid form, thus reducing the loss of antioxidant and copper inhibitor, and also the chance for thermal degradation.

2. The pigmentation is introduced in the skin, not in the foam insulation, which again improves stability and minimizes processing problems.

3. The foam insulation is protected against the filling compound by the MDPE skin.

Accelerated Ageing

The second part of the stability testing programme concentrated on measuring the change of electrical and physical characteristics of cables after prolonged ageing at 70C.

Ageing Rate - Electrical Properties. An attempt was made to determine acceleration rates for electrical ageing. Samples of foam, foam-skin and solid insulation were immersed in water baths at 25, 50 and 75C. In each bath some of each type of insulation had a constant a.c. voltage applied, some had a constant d.c., and others had no voltage applied at all. During the course of eighteen months of testing, the capacitance of the wires and the insulation resistance to the water were measured periodically.

The testing showed that the capacitance change is the same regardless of the applied voltage or lack of it during the test. All the insulations tested except the LDPE under a.c. voltage had insulation resistance substantially stable throughout the period of the test. The LDPE with a.c. voltage showed a steady decrease in insulation resistance throughout the test but with no unusual change in capacitance. This indicated that the type of incipient failure was treeing in the insulation, a familiar phenomenon in polyethylene insulated power cables.

At 75C testing, all of the samples with a.c. voltage failed during the period of the test - Foam after 32 weeks, solid LDPE after 53 weeks and foam-skin after 70 weeks. After 60 weeks the other samples of LDPE at 75C indicated failure when measured using 500V d.c. The failure was caused by thermal degradation. The remaining samples of foam and foam-skin insulated conductor have now completed 80 weeks and the test is continuing.

TABLE 9 EFFECT OF COPPER STEARATE ON THE STRESS STRAIN PROPERTIES

AGING	PROPERTY MEASURED		STABILIZER SYSTEM A		B		C		D	
			BLANK	COPPER	BLANK	COPPER	BLANK	COPPER	BLANK	COPPER
1 DAY AT 145°C	TENSILE STRENGTH	PSI	6040	5500	4930	4775	5055	4640	5040	4900
	ELONGATION	%	640	570	610	590	645	635	590	550
	TENSILE RETENTION	%		91.1		97.5		91.7		97.3
	ELONGATION "	%		89.1		96.8		98.5		93.2
	COLOUR CHANGE			NIL		NIL		NIL		NIL
3 DAYS AT 145°C	TENSILE STRENGTH	PSI	5195	DECOMP	4750	4830	4360	4250	5150	4115
	ELONGATION	%	625	DECOMP	430	550	580	540	560	500
	TENSILE RETENTION	%		DECOMP		101.1		97.5		80.1
	ELONGATION "	%		DECOMP		104.0		93.1		89.2
	COLOUR CHANGE			D. BROWN		SI.BROWN		NIL		NIL
7 DAYS AT 145°C	TENSILE STRENGTH	PSI				DECOMP	4100	4080	4960	3800
	ELONGATION	%				DECOMP	380	130	410	110
	TENSILE RETENTION	%				DECOMP		99.7		76.6
	ELONGATION	%				DECOMP		34.2		26.8
	COLOUR CHANGE					D.BROWN		NIL		NIL
14 DAYS AT 70°C IN WAX E	TENSILE STRENGTH	PSI	5476	5760	5490	5215	5350	5350	5260	5340
	ELONGATION	%	766	710	690	610	650	620	610	580
	TENSILE RETENTION	%		106.5		95.2		100		101.8
	ELONGATION "	%		92.7		88.4		95.5		95

TABLE 10 EFFECT OF 70°C AGING ON STRESS STRAIN PROPERTIES

MONTHS AT 70°C	PROPERTY MEASURED	FOAM POLYPROPYLENE									FOAM POLYPROPYLENE/M.D.P.E. SKIN					
		STABILIZER A						STABILIZER B			STABILIZER A			STABILIZER B		
		Al CONDUCTOR			Cu CONDUCTOR			Cu CONDUCTOR			Cu CONDUCTOR			Cu CONDUCTOR		
		IN AIR	IN FILL E	IN FILL F	IN AIR	IN FILL E	IN FILL F	IN AIR	IN FILL E	IN FILL F	IN AIR	IN FILL E	IN FILL F	IN AIR	IN FILL E	IN FILL F
1	TENSILE	104	103	104	113	107	111	113	103	113	95	96	96	95	91	91
	YIELD	138	126	126	132	144	127	128	111	117	114	110	109	120	118	114
	ELONGATION	88	86	82	83	73	79	84	77	79	95	96	95	93	85	88
2	TENSILE	94	103	109	111	109	114	116	92	114	93	95	97	94	91	95
	YIELD	146	133	134	136	126	130	136	115	120	124	118	120	125	119	131
	ELONGATION	64	68	82	70	65	67	73	67	70	85	83	78	76	67	72
3	TENSILE	94	105	107	111	106	111	116	110	115	92	100	101	92	91	91
	YIELD	146	137	139	137	123	125	131	117	118	126	126	126	122	122	117
	ELONGATION	64	71	74	72	63	62	75	67	64	74	78	74	78	68	72
5	TENSILE	102	104	111	111	107	108	104	101	115	105	97	101	96	92	92
	YIELD	147	127	132	138	125	126	134	106	117	121	118	121	123	122	117
	ELONGATION	75	79	77	73	68	68	79	73	76	88	88	91	84	78	87
8	TENSILE	103	107	107	101	109	112	110	105	111	92	96	97	88	88	91
	YIELD	152	133	135	117	113	117	136	125	124	125	123	121	115	121	120
	ELONGATION	76	76	81	75	66	73	70	65	68	85	83	87	85	75	77

NOTE: VALUES ARE PERCENTAGE RETENTION OF UNAGED SAMPLES

From analysis of the data it was found that the rate of capacitance increase doubles every 10C increase in temperature and that the acceleration rate is the same for foam, foam-skin and solid insulation.

This information allowed Fig. 12 to be completed so that both the physical and electrical ageing are included as a function of mean annual temperature.

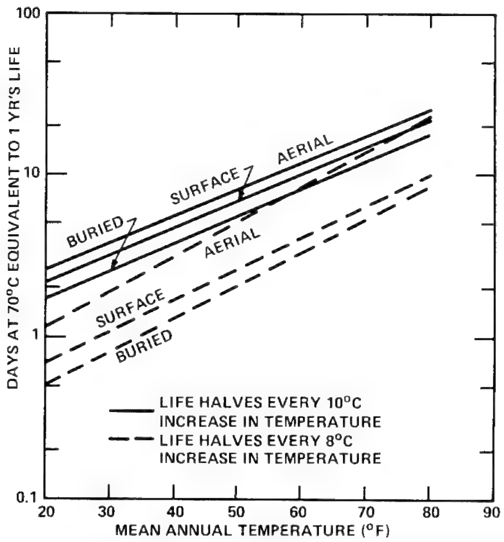


FIG. 12 TESTING REQUIRED AT 70°C FOR PHYSICAL & ELECTRICAL LIFE AS A FUNCTION OF MEAN ANNUAL TEMPERATURE

The other information gained from the testing of the insulation under water is that the change of capacitance is a function of the average density of the insulation. At any temperature, for a given change in capacitance of the foam insulation, the foam-skin insulation took three times as long to make the same change and the solid insulation took 10 times as long. These insulations had percentage air content "blows" of 35%, 20% and 0% respectively. Electrically, however, the two expanded dielectrics were almost the same - 30% equivalent blow for the foam-skin and 35% blow for the foam. Thus the foam-skin should be more stable over any given period compared to a foam insulation. In a later section, this is shown to be true for cables.

Comparison of Physical and Electrical Ageing. There is one important difference between the two sets of graphs in Fig. 12. The rate of electrical ageing shows that if a change occurs after a certain time at a test temperature, then the same change will occur after a time which doubles every 10C decrease from this test temperature. The rate of physical ageing, however, is based upon completion of the useful physical life of the insulation. The failure of all of the LDPE samples physically at 75C indicates a maximum life for the insulation of between 25 and 30 years when exposed to the sun at a mean annual temperature of 75F, and this life could be shorter if the insulation is stressed. For this insulation, the emphasis on physical life is correct.

We see in Fig. 11, however, that the insulation system being used in the filled foam-skin insulated cable is stable for a decade longer than the LDPE, and it is not anticipated that physical degradation will be a problem during the service life of this insulation system. Changes which occur in the electrical characteristics of the cable, however, could change the transmission properties of the cable to such a point that there is a serious degradation in the quality of the telephone service. Useful electrical life will have to be defined as the time taken for these properties to change such that they start to have an effect on the quality of transmission.

Extended Testing at 70C - Physical Ageing

Copper and aluminum insulated conductors were aged in a 70C air oven for 8 months. The insulations were foam and foam-skin with both the A and B stabilizer systems incorporated in the foam polypropylene. The samples were aged in air and in filling compounds E and F. Periodically samples were removed from the oven, allowed to cool and tested for tensile strength, yield, elongation, and change in weight and diameter.

The values in Table 10 show that after 8 months ageing, the samples in both filling compounds changed very little from their original values. Similar testing of cable insulations during the electrical tests showed these insulations to be stable for 18 months at 70C.

This result would be expected from the results of testing at 145C in Table 9. Assuming that the rate of ageing doubles every 8C increase in test temperature, 1 day at 145C is equivalent to 2 years at 70C. Testing at the lower temperatures (70C) gives more confidence in the short time high temperature tests, and, 70C was chosen because at higher temperatures the filling compound starts to become liquid.

From Fig. 12, 8 months physical ageing at 70C is equivalent to about 20 years life aerially at a mean annual temperature of 68F, and 1 day at 145C is equivalent to 50 years aerially at 68F ambient. The system presently being used lasts 7 days without becoming brittle, which indicates that the system is suitable for long life at high ambient.

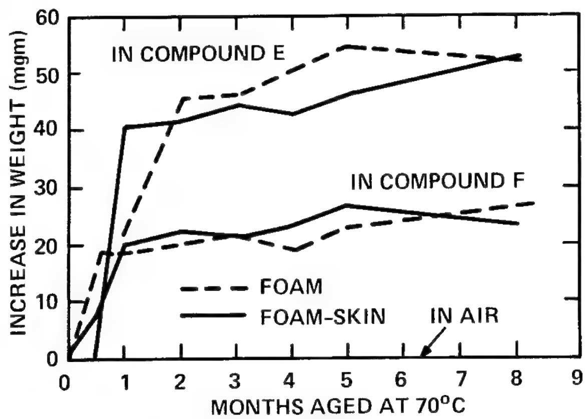


FIG. 13 CHANGE IN WEIGHT OF INSULATION

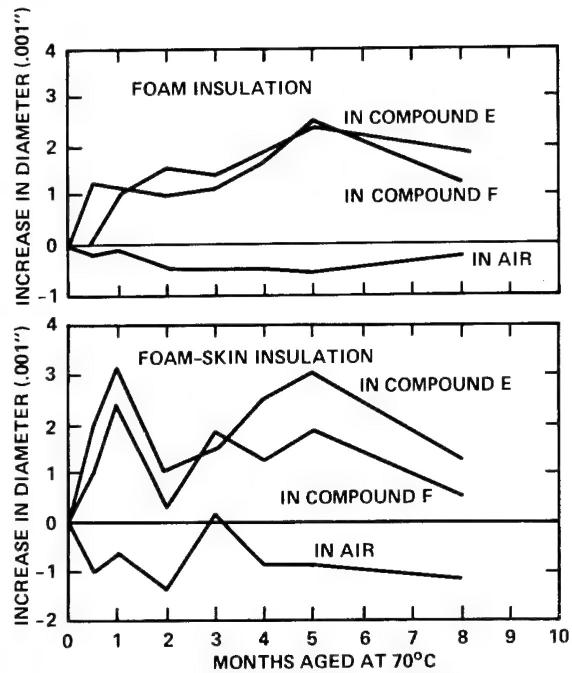


FIG. 14 CHANGE IN DIAMETER OF INSULATION

The changes of the other two properties measured - weight and diameter are shown in Figs. 13 and 14. Any change takes place during the first 2 months of testing and then stabilizes. It can be seen that both the foam and the foam-skin insulations absorb the same weight of filling material. The filling compound F caused a smaller increase in weight than the compound E. The increase in diameter caused by the two filling compounds was the same for the foam and the foam-skin insulations, and it would be expected that these changes would reflect in the electrical ageing of the complete cables.

Extended Testing at 70C - Electrical Ageing

To determine the changes in electrical properties with ageing, lengths of sealed sheath cable, each with a different combination of insulation and filling material, were immersed in water leaving only the ends out. The water bath was heated to a temperature of 70C and held steady at that temperature. The water acted as both the heating medium and to simulate moist soil conditions. The transmission properties were measured on one length of each type of cable. Other lengths of each type were also immersed so that samples could be cut from them periodically. Changes in those properties measured by destructive tests could then be monitored.

The changes in tensile, elongation, yield, weight and diameter of the insulated conductors measured agreed with the changes measured in the oven tests for 8 months, indicating that the two tests were ageing the materials similarly. After 18 months the tensile, yield and elongation still showed no indication of degradation. Further evidence that the 145C test may be a valid test for extrapolation back to ambient temperature.

One of the cables being tested was a regular unfilled PIC cable with LDPE insulation - similar to that used for the study on electrical ageing. After 18 months, the insulation from this cable still had over 90% retention of tensile strength and elongation. It would seem from this that although samples of LDPE exposed to the air during its use (such as in above ground) pedestals) may become brittle, similar insulation with its jacket still in place will remain flexible after extended ageing.

Change in Primary Properties. Over the 18 months that the tests have been running to date, the regular unfilled PIC cable and a cable made using solid polypropylene with no filling exhibited stable values of primary parameters over the frequency range 1 kHz to 772 kHz. This is another indication that the retention of physical properties of regular PIC is more important than the stability of electrical properties, and that the emphasis placed on thermal stability in the past was justified.

With filled cables, however, we have stable physical properties over long periods of time, but Figs. 15, 16, 17 and 18 indicate that the stability of transmission properties require specific consideration, since these are the properties which are

most likely to change. Solid MDPE, the present Canadian standard for solid filled cables, was stable over the whole test with filling compound E. With cellular insulations, Fig. 15 shows how important the choice for a proper filling compound is. Obviously filling compound G, which is 100% petrolatum, is not suitable for use with a foam insulation if long time stability is required. Compound F is the most stable of the three compounds tested, but it was not selected because it was not acceptable for handling in manufacturing and splicing. The decision was made therefore to use compound E. This is the compound whose use is described in the section on filling the cable core.

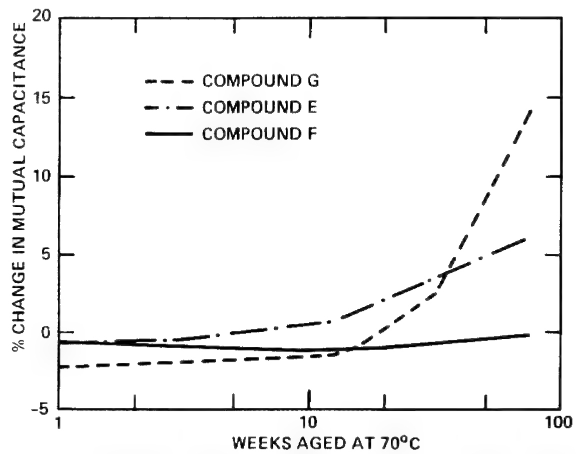


FIG. 15 CHANGE IN MUTUAL CAPACITANCE (ALL INSULATIONS FOAM P.P.)

The decrease in mutual capacitance over the first month of testing could be anticipated from the data in Figs. 13 and 14. The filling compound is absorbed by the insulation, causing it to swell. Because earlier tests showed the weight and diameter are constant from the third month, the increase in capacitance shown after 2-3 months must be caused by the compound filling the cells of the foam insulation after saturating the polymeric insulation.

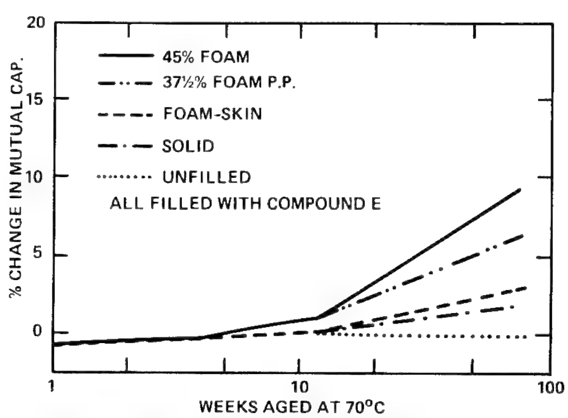


FIG. 16 EFFECT OF BLOW ON CHANGE IN MUTUAL CAPACITANCE

The increase in capacitance is confirmed as a function of the density of the insulation - Fig. 16 and Fig. 17. The foam-skin has the advantage over the foam insulation because gravimetrically its blow is about 20% that of the solid insulation, and electrically it is equivalent to a foam insulation with 30% blow. The use of the composite insulation is, in effect, acting to slow down changes in the electrical properties.

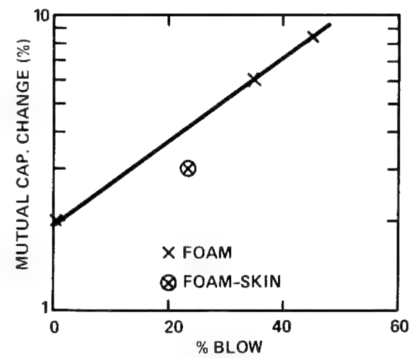


FIG. 17 RELATIONSHIP % BLOW AGAINST % MUTUAL CAPACITANCE CHANGE AFTER 74 WEEKS AT 70°C (FILLING COMPOUND E)

The changes in conductance shown in Fig. 18 were not considered to be too important to the transmission properties of the cable, except for the sample with compound G. This was checked by routine measurement of attenuation at 3.2 MHz. The only cable where attenuation was not stable was that using the G filling compound, which increased by 50% over 18 months.

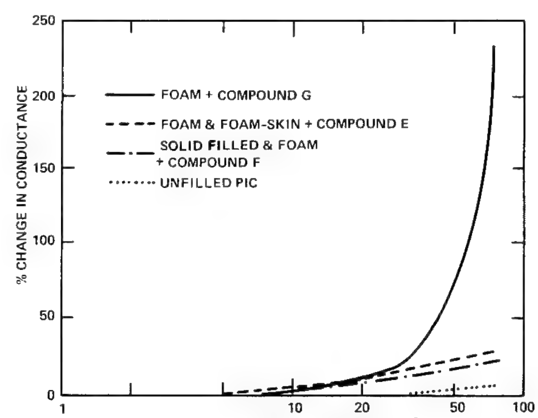


FIG. 18 CHANGE IN CONDUCTANCE WITH AGING AT 70°C

Change in Other Electrical Properties. The dielectric breakdown strengths of the foam-skin cables were stable over the whole period of the test, as was the filled MDPE and the regular LDPE. Degradation of the foam and LDPE cables can be seen from the

insulation resistance graphs in Fig. 19. The filled foam-skin and the MDPE are substantially stable.

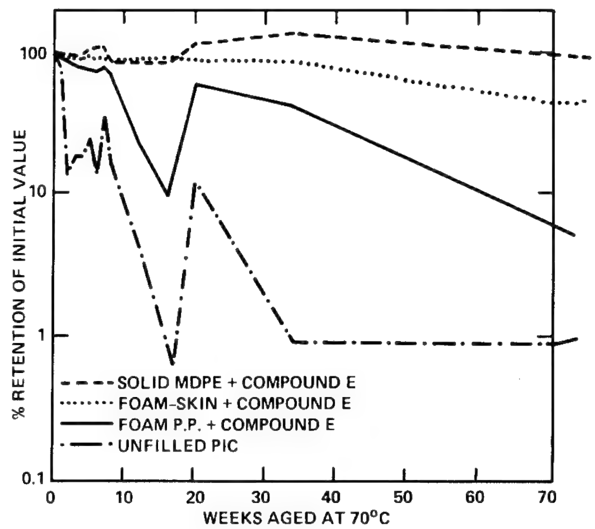


FIG. 19 CHANGE IN INSULATION RESISTANCE WITH AGING

Conclusions

Foam-skin insulated, fully filled cables, Migrabloc F/S(R), are completely interchangeable with filled cables using solid insulation, and will meet the same requirements. During manufacture, the foam-skin insulation process is both easier to control, and will result in lower scrap, than when foam alone is used. It is anticipated that the absence of pigment in the foam portion will extend the insulation service life. Further, the solid skin over the foam protects it from the filling medium and retards changes in the electrical properties of the cable.

Acknowledgements

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A PROCESS OF MANUFACTURING FOAMED POLYETHYLENE INSULATION BY USING LOW HYDROCARBON AS BLOWING AGENT

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Summary

A process of manufacturing foamed polyethylene(PEF) wire insulation using low hydrocarbon as blowing agents was investigated. For this purpose, a front-end drive extruder was developed. It was found that the shape and arrangement of a die and wire guider was most important in obtaining a good PEF insulated wire with this process. As an example, a PEF insulation with 0.1 mm wall thickness and 40 % expansion on a 0.5 mm dia. copper conductor was formed at the manufacturing speed of 800 m/min and an alpeth cable of 100 pair cable was made of those wires. Electrical measurements showed that the electrical characteristics of this cable were almost the same as those of a paper insulated cable with the same conductor dia. as the cable prepared. This process has the following advantages: (1) The closed-cells in the insulation are smaller than those in the insulation produced by chemical blowing agents. (2) The insulation does not contain any bubble nucleator.

Introduction

Looking into the history of wire insulation for a communication line, it will be found that insulation has changed from paper to solid polyethylene and then to foamed polyethylene, which may be considered as the most feasible replacement for paper in the near future. There are several processes for the manufacture of foamed polyethylene insulation. No process, however, suited for producing fine-celled foamed polyethylene insulation on a wire around 0.5 mm in diameter had yet attained commercial status in 1964 when this developmental research commenced in N. T. T. In those days, it was found from experiments with an autoclave that a good foamed polyethylene containing many fine cells was obtained by using propane as a blowing agent without any bubble nucleator or bubble initiator. Although foamed polyethylene without the residue of blowing agents is obtained when gas is used as a blowing agent, at that time efficiency of expansion had made it difficult to produce thin-walled wire insulation. Hansen et al.[1] reported that fine-celled foamed polymers are obtained by using a trace amount of materials such as metal particles and exothermal chemical nucleators with nitrogen gas. Also, there are several patents[2] on a process for producing foamed materials by the use of several different kinds of gas as blowing agents. In these processes, different kinds of bubble nucleators are used to obtain fine-celled foamed materials effectively. However, these nucleators have an adverse tendency on the electrical characteristics of the insulation.

For those reasons, on the basis of the preliminary experiments with the autoclave, investigations have been made of a process for producing foamed polyethylene insulated wire containing numerous fine closed-cells by using nothing but low hydrocarbon as a blowing agent.

The parts relative to the preliminary experiments and foaming process in these investigation have been already reported in the 19th I. W. C. S.[3] Accordingly, this paper is mainly concerned with the process for manufacture of foamed polyethylene insulated wire.

Extruder

In these experiments, a front-end drive extruder was used. Figure 1 shows the main difference between this extruder and a conventional one.

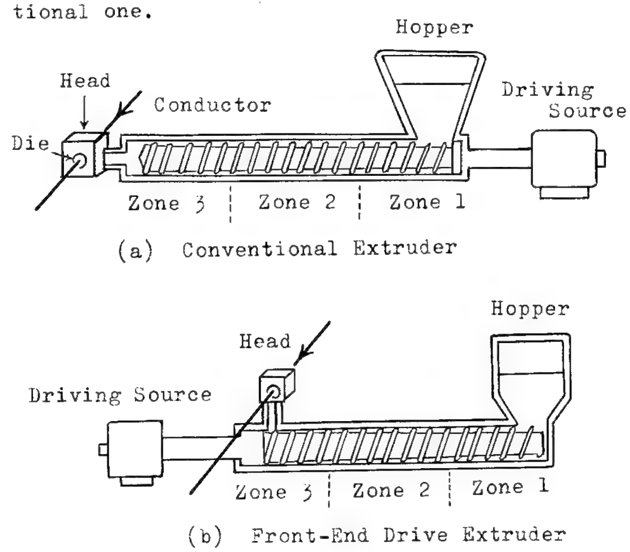


Fig. 1 A Conventional Extruder and a Front-End Drive Extruder

At first, a series of preliminary experiments was carried out with a conventional extruder, but it soon became evident that it was difficult to prevent the leakage of the hydrocarbon used as a blowing agent from the clearance between the screw-shaft and the barrel of the extruder. For this reason, a new extruder, which has a screw driving source at the head end and a pressure hopper at the other end was developed, called a "front-end drive extruder". This type of extruder has several advantages, which have been described by M. Egar[4]. Furthermore, it has the following advantages: The hopper side of the extruder is hermetically sealed and hydrocarbon leakage at the head side is prevented by the molten polyethylene oozing from the clearance between the screw-shaft and the barrel.

The screw of the developed extruder is 50 mm in diameter. It is a metering-type with constant pitch. The ratio of the barrel length to the diameter of the barrel is 24. Figure 2 is a photograph of the pressure hopper of the extruder. The hopper consists of two pressure

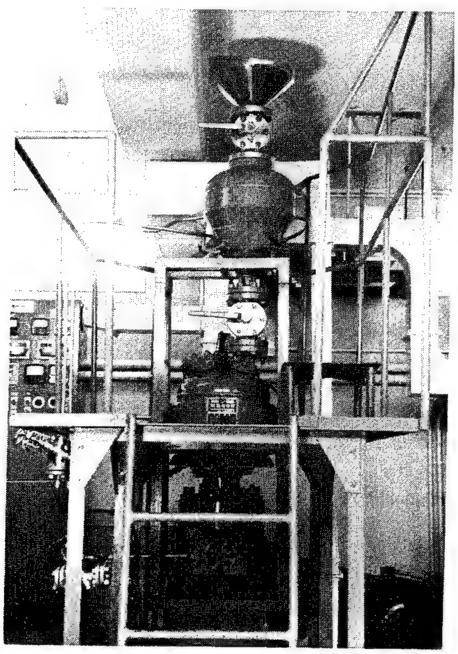


Fig. 2 Continuous Feeding Hopper

containers, an upper container and lower one. A ball-bulb is installed at the upper side of each container to feed material continuously. The inner volume of each container is about 50 liters. Each of them can resist up to 50 kg/cm^2 in pressure. Heating of the extruder is controlled at five zones, three zones on the barrel and one zone each on the head and the die, respectively. The barrel heaters are cast heaters with air blowers installed on each zone. The barrel in the feed section is cooled with cold water to prevent sintering of plastic materials and boiling off of fed hydrocarbon. The head heater is a cartridge heater and die heater is a cast heater.

The low hydrocarbons are fed through the pressure hopper. When the hydrocarbons are gaseous during feeding, they are fed through some reducing valves, and, when they are liquid, through some forcing pumps. Further on account of using low hydrocarbon as blowing agents, many safety plans are considered, such as the use of explosion-proof switches, installation of alarm devices and ventilation of the control panel and laboratory.

Factors for Manufacture

The following manufacturing factors were investigated.

Extruder Temperatures

In the barrel just under the hopper, the hydrocarbon and the polyethylene are in a just mingled condition. For this reason, the barrel temperature just under the hopper was controlled so as not to boil hydrocarbon fed when it was liquid. The temperatures of other sections were widely varied on the basis of conventional extruder temperatures.

Die and Wire Guider

Figure 3 shows a cross section of a die and wire guider. As a copper wire 0.5 mm in diameter was used in these experiments, the orifice of a wire guider was 0.55 mm in diameter. Dies and wire guiders were made of steel or stainless steel, and these tips were made of a very hard metal. The die orifices used in the experiments were varied from 0.58 to 1.0 mm in diameter, and die land lengths from 0 to 25 mm. In addition, several factors pertaining to manufacture in relation with dies were investigated.

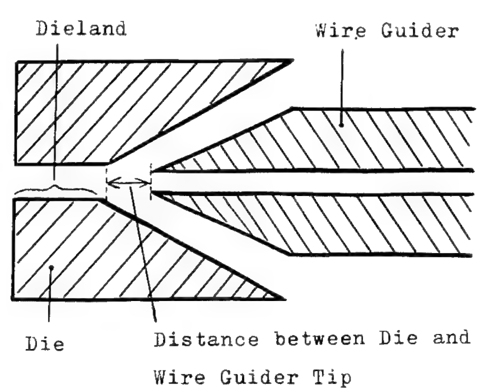


Fig. 3 Diagram showing the Conventional Relation between a Die and a Wire Guider

Hydrocarbon and Pressure in Hopper

Based on the fact that bubble nucleators had hitherto been used to form foamed polyethylene having numerous fine cells, it was considered that it might be necessary for polyethylene to contain a large amount of hydrocarbon in order to form numerous fine cells in polyethylene in the absence of the nucleators. On that account, methane and propane, which are in the same group with polyethylene, were used. When the hydrocarbon was propane, the pressure in hopper was varied from 6 to 18 kg/cm^2, and when it was methane, from 15 to 50 kg/cm^2. In this case, a hopper which was proof against 120 kg/cm^2 pressure was used.

Polyethylene

Two kinds of low density polyethylene(M.I.=1.2 and 0.25) and a high density polyethylene (M.I.=0.3) were used.

Line Speed and Screw Speed

The amount of polyethylene on a conductor mainly depends on a line speed and screw speed. As it was ascertained that the amount extruded from a extruder was directry proportional to the screw speed, the following ratio:

$$\frac{S}{L} = \frac{\text{Screw Speed (rpm)}}{\text{Line Speed (m/min)}}$$

was defined as a parameter of the amount of polyethylene on the conductor. Furthermore, several factors, such as cooling of and preheating of the conductor, as well as quenching and mild cooling of the insulation just after extrusion, were investigated.

Evaluation of Foamed Polyethylene Insulation

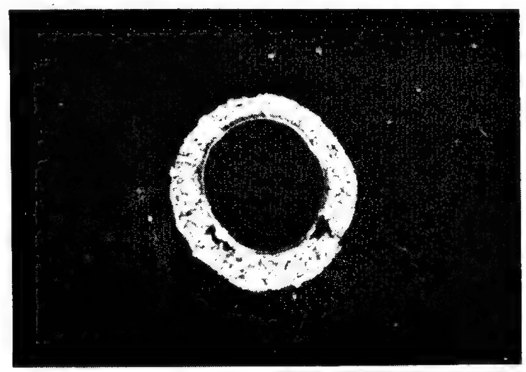
In the experiments, the following characteristics were mainly made the objects of evaluation for the foamed polyethylene insulation.

Outside Diameter, Inside Diameter and Thickness of Insulation

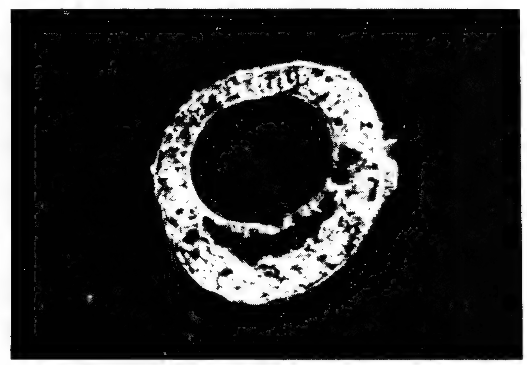
The insulation pulled out from the wires was cut down in round slices of a few tens microns in thickness perpendicular to the major axis with a safety razor blade or a microtome and then the outside diameter, the inside diameter and the thickness were measured with a microscope from their cross sections. In the latter preparation, the round slice samples were made as shown below. First, the insulation was buried in polyvinyl alcohol or a few percent aqueous solution of sodium alginate, and then frozen and cut down. Then, the samples were buried into polyethylene glycol on a glass plate and measured.

Void and Double Insulation

A larger space than that around the cells in the cross section of the insulation was named a "void", and when space larger than the void was formed in the insulation and looked like forming double insulation, the phenomenon was named "double insulation". Figure 4 shows an example of a void and a double insulation.



(a) Void



(b) Double Insulation

Fig. 4 Void and Double Insulation

Expansion Degree

With consideration for pinholes or asymmetry of thickness in the insulation, the degree of expansion was calculated as the following:

Expansion Degree

$$= 1 - \frac{\text{Weight of Foamed Insulation}}{\text{Weight of Solid Insulation having the Same Volume as Foamed Insulation}}$$

Furthermore, the figure of the cross section of the insulation, bubble size distribusion, surface smoothness and elongation of and shrinkage of the insulation were measured.

Dependence of the Properties of the Insulation on the Factors for Manufacture

Using Methane as a Blowing Agent

When the methane pressure in the hopper reaches 15 kg/cm², comparatively large cells form just one layer around a conductor. When the pressure rises to more than 15 kg/cm², not only is the cell size large, but also the number of cells decreases. When the pressure rises to more than 40 kg/cm², the cells are diminished uniformly, the inside diameter of the insulation increases and do not fit a conductor. This tendency hardly changes, even when other factors for the extrusion process are changed. Figure 5 shows an example of a cross section of the insulation when using methane.

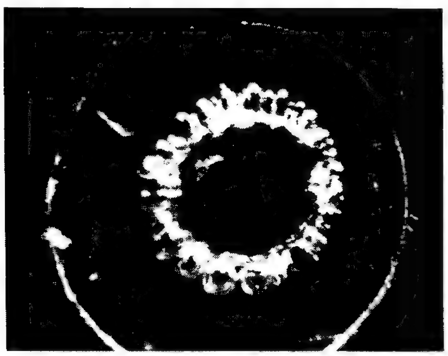


Fig. 5 Cross Section of the Insulation with Methane as Blowing Agent

Using Propane as a Blowing Agent

Pressure of Propane in the Hopper

If the extrusion conditions are proper, it may be found that numerous fine closed cells are formed all through a cross section of the insulation at a pressure of about 10 kg/cm². At a pressure of from 10 to 18 kg/cm², there are no special changes. Over a pressure about 18 kg/cm², the surface smoothness decreases.

Polyethylene

When low density polyethylene with a 1.2 melt index is used, the cell size is about 10 microns in diameter. Using low density polyethylene with a 0.25 melt index, the cell size becomes a little larger, increasing to 20～30 microns in diameter, but pinholes are seldom found and surface smoothness is improved. When 1.2 melt index low density polyethylene is blended with 0.25 melt index low density polyethylene of about 10 weight percent on the total weight of polyethylene, the cell size is not only as small as about 10 microns in diameter, but also pinholes are seldom found and surface smoothness is improved. When a high density polyethylene(M.I.=0.3) is used, almost the same insulation as one of low density polyethylene is obtained, though the extrusion speed has to be lowered to one tenth as compared with low density polyethylene extrusion speed.

Extrusion Temperature

The best extrusion temperature for extrusion of low density polyethylene with lower melt index is a series of temperatures of 140°C in cylinder zone 1, 200°C in cylinder zone 2, 280°C in cylinder zone 3 and 280～300°C in head and die (c.f. Fig.1). Although melt viscosity of polyethylene containing propane remarkably drops, more powerful extrusion power is required when a die orifice or a distance between a wire guider and die decreases. In these experiments, therefore, the extrusion temperature was made a little higher than usual to decrease the load of the drive motor.

Die Shape

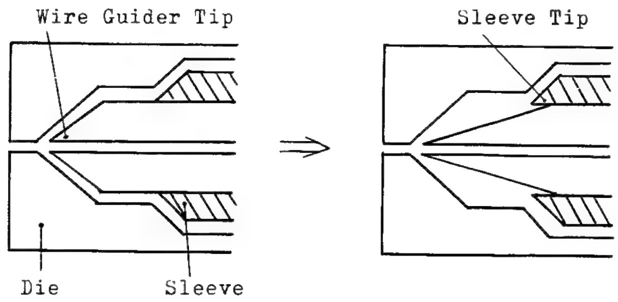
When the die orifice becomes larger, voids and double insulation are liable to be formed. A straight-land die land seems to be better than a taper-land. When die land lengths become shorter, the tightness of the insulation on the conductor tends to result in improvement, but surface smoothness deteriorates.

Wire Guider

When the distance that the wire guider tip projects behind the rear edge of the die land is too short, foamed polyethylene blows off from the die in the powder state. Being too long, the tightness of the insulation becomes wrong, though the surface smoothness becomes better. The most desirable distance is about 0.5～1.0 mm. When coating solid polyethylene on a conductor, the arrangement die and wire guider have generally been made as shown in Figure 6-(a), but, in these experiments, good tightness of the insulation on a conductor could not be obtained in such an arrangement. The best arrangement was that shown in Figure 6-(b).

Conductor Preheating

Using a heated conductor with high melt index polyethylene, the tightness of the insulation is improved, but most cells in the insulation disappear in the process. Using a conductor with low melt index polyethylene, elongation of the insulation increases and the cells remain intact, but the tightness of the insulation decreases.



(a) Conventional (b) Developed

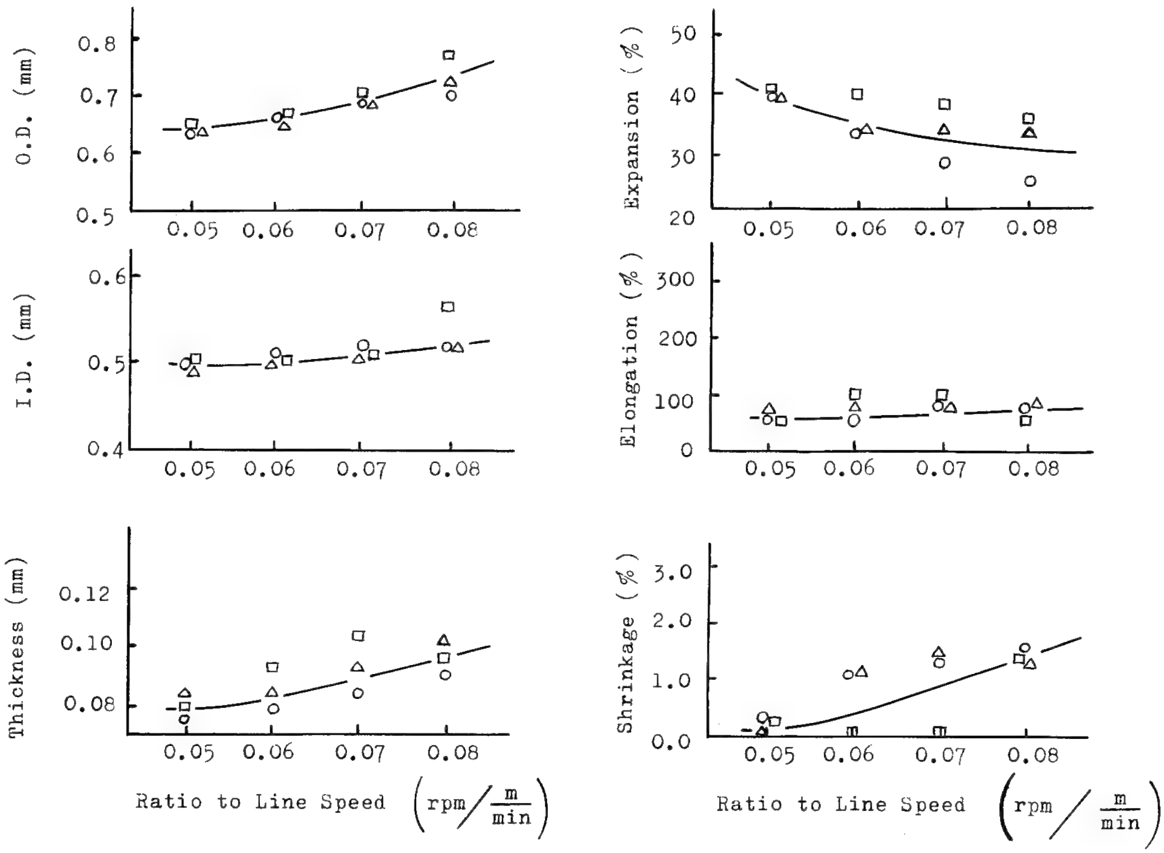
Fig. 6 Diagram showing Die and Wire Guider Arrangement in the New Method

Ratio of Extrudate to Line Speed

With an increase of the extrudate to line speed ratio, the outside and inside diameter, wall thickness and shrinkage of the insulation tend to increase, but insulation expansion tends to decrease. Elongation of the insulation scarsely changes. Figure 7 shows an example of the dependence of the several properties of the insulation on the ratio to line speed.

Discussion

In a preliminary experiment, good foamed polyethylene in noodle shape was obtained. From this result, it did not appear to be difficult to produce a good foamed insulated wire. But, in coating the foamed polyethylene insulation on a conductor by extrusion, many problems emerged in practice.



Line Speed

○ : 400 m/min
△ : 600 m/min
□ : 800 m/min

Extrusion Temperature

Tc = 140 °C
Tc = 200 °C
Tc = 280 °C
Th = 280 °C
Td = 320 °C

Diameter of Die orifice : 0.6 mm
Dieland : 1.0 mm
Distance between Die and Wire Guider Tip : 1.0 mm

Fig. 7 Dependence of Developed Foamed Polyethylene Insulation on the Ratio of the Extrudate to Line Speed

First, it was attempted to form the foamed polyethylene insulation on a conductor by the use of methane as a blowing agent without any bubble nucleator. However, finer cells than those generated by the use of propane could not be formed in the insulation. Therefore, only propane was used in subsequent experiments. Using propane, fine celled foamed polyethylene insulation has been obtained, but the problems such as pinholes, double insulation, voids and slackness of the insulation fit had emerged. Double insulation was eliminated by making the die orifice smaller, and both pinholes and voids were almost completely eliminated by the use of polyethylene with a proper melt index. But the most difficult problem was improvement of the tightness of the insulation on the conductor. Considering the "hot spot effect" which Hansen and others advocated, it was attempted to extrude the insulation on a cooled conductor. But the tightness of the insulation was not improved.

The foaming process on this method was considered again. From the extrusion of the insulation at various pressures of propane in the hopper, the following results were found: (1) At a pressure below 10 kg/cm^2 in the hopper, few cells were formed in the insulation and nothing was obtained but a solid insulation with a slack fit on the conductor. (2) When the pressure became about $10\sim12$ kg/cm^2, cells were formed all through the cross section of the insulation and the degree of expansion scarcely altered when the pressure was made more higher than the values listed above. (3) When the pressure decreased from a high one(18 kg/cm^2), cells suddenly ceased being formed in the insulation at a pressure of around 10 kg/cm^2 , the outside and inside diameter of the insulation became rather larger than that of a foamed insulation and the wall thickness became rather thin.

This phenomenon shows that propane which is not spent to form cells contributes to increasing the diameter of the insulation. On the other hand, when the insulation in which cells are formed was obtained, regardless of extrusion temperature and the propane pressure, cells are observed all through the cross section and there is hardly difference in the degree of expansion. From these facts, it is concluded that, in this method, there is a certain minimum pressure of propane necessary for forming cells and, at a pressure over the minimum, the polyethylene is foamed to near the expansion limit which is decided by manufacturing factors other than propane pressure.

In this method, where cells are formed without a special bubble nucleator, it has not been explicitly shown what a bubble initiator is. It was assumed that it would probably be the extremly fine spots where heavy concentration of propane is caused by inferior dispersion of propane in the molten polyethylene. On basis of the experimental results described above, this foaming process is assumed to be as follows: (1) A larger amount of propane than necessary to cause cell growth is necessary to create bubble initiation spots without any bubble nucleator. (2) After the bubble initiators are created, the amount of propane greater than is necessary to make cells grow becomes excessive, and it separates from the polyethylene containing bubble initiators. (3) The separate propane is released and the propane contributing to the growth of cells is substituted for by air after cells have grown.

Presuming a foaming process described above, in case this foaming process is carried out with a conventional extrusion method(shown in Figure 6-(a)) where the polyethylene containing propane is gradually compressed all on the way to the exit of a die, it follows that the bubble initiators are created just after emerging from a die. Consequently, the excess propane in the cell growing process separates from the polyethylene after formation of the insulation on a conductor, and the propane passing through to the internal surface of the insulation forms a gap between the insulation and conductor. Also, as described above, when the propane pressure is lower, only a solid insulation having slack wire contact is formed. This fact, according to the assumption described above, may be explained as follows. The propane which ought to be expanded for the growth of cells just after emerging from a die has merely separated from the insulation without contribution to foaming, because the polyethylene does not contain enough propane to create bubble initiation spots. Consequently, compared with case of foaming, the amount of propane passing through to the internal surface of the insulation increases and a large gap is formed between the insulation and conductor.

Therefore, in order to improve the tightness of wire contact, a die and wire guider set was arranged as shown in Figure 6-(b). This arrangement aims at the following. As soon as the polyethylene containing propane, which is gradually compressed all on the way to the tip of the sleeve through the head of the extruder, is extruded in the larger space enclosed with the die and wire guider, it is rapidly made to expand a little. Consequently, the spots of bubble initiation are created there and the excess propane on the growing process is made to separate. Then the insulation is formed through the dieland, while the separated propane passes out along the inner surface of the die and dissipates in the air. As a result of experiments, a fine celled foamed polyethylene insulated wire with good tightness of the insulation on the conductor was obtained. Figure 7 shows several characteristics of one of the insulations obtained.

The following presumption was formulated: If the space enclosed with a die and wire guider is filled with polyethylene, tightness of wire contact may decrease again because polyethylene expansion may not occur in that space. Following that reasoning, manufacturing of the insulated wire was continued for an hour and a good foamed polyethylene insulated wire was continuously obtained, as shown in Figure 8. This may

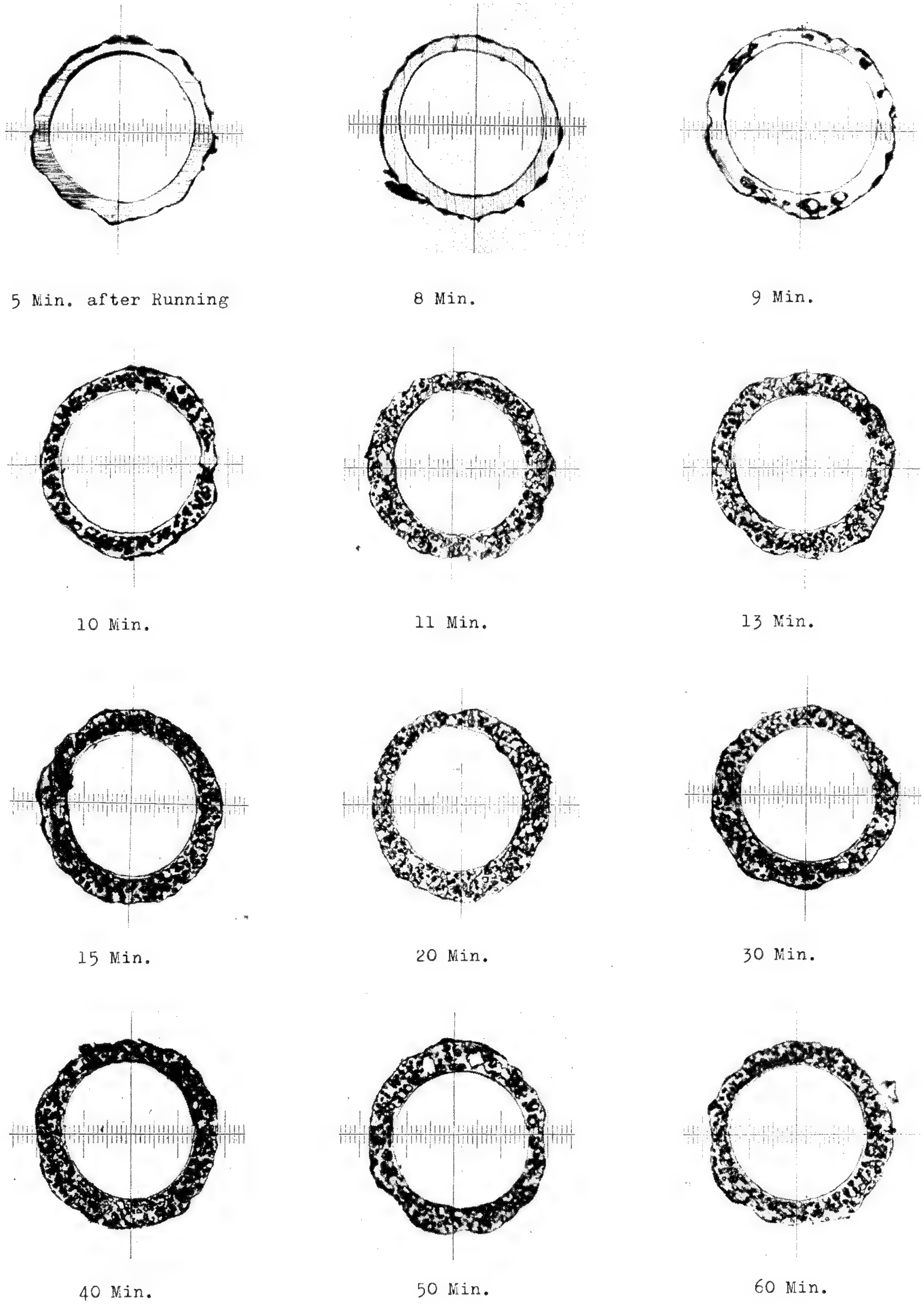


Fig. 8 Stability of Continuous Manufacturing of Thin-Walled Wire Insulation

result from the fact that polyethylene containing propane will have a rather smaller bulk modulus compared with polyethylene not containing propane. Further details of the analysis of this foaming method will have to be done in the future.

A good insulated wire coated with a thick foamed polyethylene has not yet been obtained by the use of this method. Figure 9 shows one result obtained by this method. Though several voids can be seen in the cross section of the insulation, where it is presumed that some cells gather and formed them, good wire insulation will soon be obtained by control of raw materials and the extruder conditions.

Fig. 9 Cross Section of Thick Walled Wire Insulation

Trial Cable and Transmission Characteristics

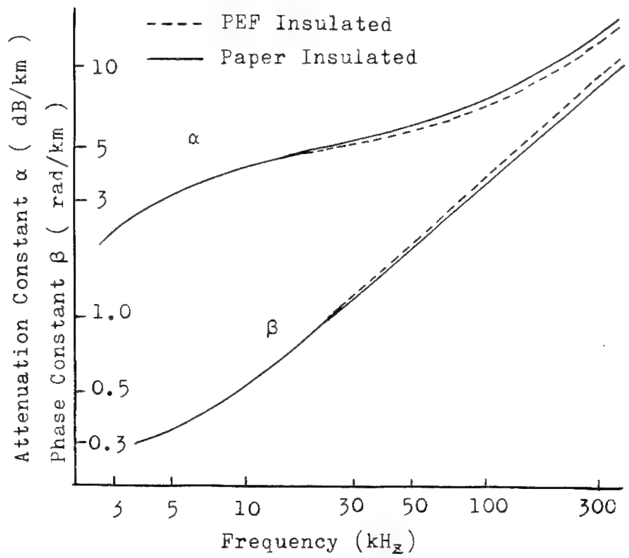
In order to examine the various characteristics of the insulated wires which are made into a cable, a 100 pair alpeth cable was experimentally produced with the insulated wires 0.5 mm in diameter. Table 1 and Figure 10 show the insulation chatacteristics of the cable cores and the transmission characteristics of the cable, respectively. Though the secondary constant of the cable tends to become a little inferior to that of paper insulated cable in a high frequency range, it can be said that there is hardly any difference between them in the voice frequency range.

Conclusion

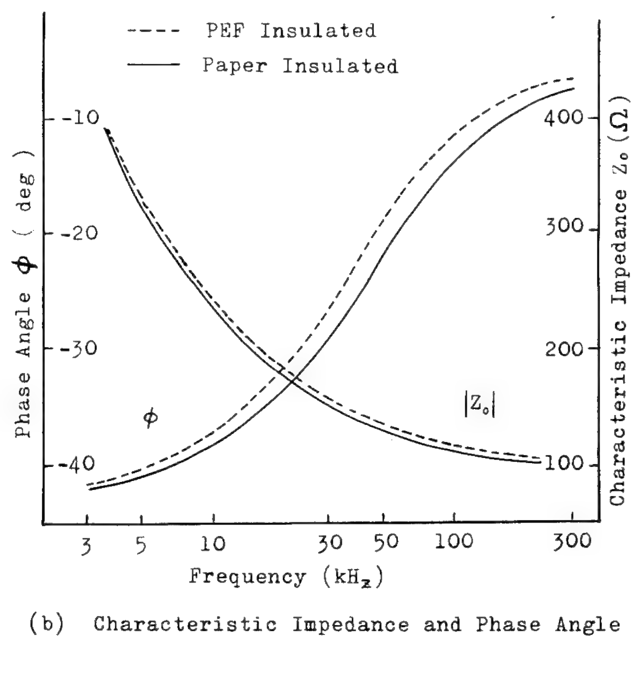
Good insulated wires with fine-celled foamed polyethylene having closed cells could be obtained by the use of propane as a blowing agent without any bubble nucleator or bubble initiator. It was found that the transmission characteristics of cable made up of insulated wires insulated by the new foaming method was almost the same as of that paper insulated wires. The foamed polyethylene insulation

Table 1 Some Characteristics of the Foamed Polyethylene Insulated Wire for a Trial Cable

Outside Diameter	0.7 mm
Inside Diameter	0.5 mm
Wall Thickness	0.1 mm
Expansion	30 percent
Av. Dia. of Cells	20 micron
Elongation	100 percent



(a) Attenuation Constant and Phase Constant



(b) Characteristic Impedance and Phase Angle

Fig. 10 Secondary Constant of the Trial Cable

obtained with the foaming method described in the paper does not contain any nucleator or initiator, any residue of a chemical blowing agent itself or any decomposition residue. Consequently, this insulation can be said to be suited for use in a rather high frequency range, too.

Acknowledgements

The authors wish to thank Dr. Kisaku Nakagawa for his useful guidance, the engineers of the Hijiri Manufactory Inc. for their cooperation in the design and development of a front-end drive extruder and to many colleagues involved in this work for their cooperation.

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EXTRUSION OF TELEPHONE CABLE INSULATION USING EXPANDABLE MEDIUM DENSITY POLYETHYLENE COMPOUNDS

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ABSTRACT

Extrusion techniques for producing Cellular Telephone Singles Insulation from specifically designed polyethylene compounds containing an azodicarbonamide type blowing agent are described. Activation characteristics of the blowing agent are related to extrusion melt temperature. Expanded density, cell structure, electrical and mechanical properties of the insulation are optimised during extrusion.

INTRODUCTION

Cellular polyethylene has been successfully adopted for the insulation of unfilled and petroleum jelly filled telephone distribution cables in the United Kingdom network(1). Conversion of suitable expandable compounds is carried out on high speed extrusion equipment as used for solid low density polyethylene insulation. A desirable feature is an extruder screw profile modified to avoid excess shear, and therefore temperature increase in the compound. Good control of applied screw and line speeds and of applied temperature is essential to avoid variable expansion. Essential requirements are:-

1. Conductor preheat to develop adequate mechanical performance.

2. Accurate melt temperature control to within 1°C. to ensure uniform expansion behaviour.

3. In line capacitance measurement to ensure the correct degree of expansion and to monitor quality control.

EXPANDABLE MEDIUM DENSITY POLYETHYLENE COMPOUNDS

Compounds suitable for the application are specifically formulated to achieve the correct degree of expansion at high line speeds without melt fracture(2). To achieve adequate mechanical properties, crush resistance and chemical resistance, the unexpanded polymer density is normally in the range 0.935 - 0.940 (ASTM D1505). The compounds contain a chemical blowing agent which activates during extrusion to provide the cellular structure. With such materials a smooth surface at 1650 metres/minute (5,000 ft./minute) is achieved with conductors of 0.5 mm. (AWG 24) diameter. This performance demonstrates that line speeds obtained with cellular polyethylene insulation are fully comparable with solid polyethylene and are eventually terminated by equipment rather than compound limitations. The techniques reviewed are related to compounds specially formulated for the application(2).

RELATIONSHIP OF CELL STRUCTURE AND EXPANDED DENSITY

The cell structure of compounds containing chemical blowing agents is optimised, on extrusion, at a temperature immediately above their activation temperature. To ensure a fine cell structure with the polyethylene compounds considered, an azodicarbonamide type blowing agent is used. This blowing agent optimises cell structure at temperatures between 220 and 225°C., which is ideally the required melt temperature of extrusion. To achieve satisfactory electrical properties (capacitance) a specific gravity of 0.50 - 0.65 and desirably 0.55 - 0.60 is necessary. Figure I shows that by careful selection of blowing agent type and content, the optimum cell structure and required specific gravity are obtained at an extrusion melt temperature 220 - 225°C. Higher temperatures produce a coarse cell structure in which the specific gravity is initially lowered but subsequently increases as expansion capability is lost.

The die diameter should allow for the degree of expansion required (Appendix 2).

CAPACITANCE AND SPECIFIC GRAVITY

The specific gravity of cellular polyethylene insulation is directly related to capacitance. A specific gravity of 0.55 - 0.60 achieves the mutual capacitance requirements of telephone cables to U.K. specifications(3), and it is expected these will not differ significantly in other countries. With the particular conductor dimensions and insulation wall thickness range this converts to a capacitance range of approximately 45 - 60 pf/ft. (148 - 198 pf/metre).

EXTRUSION

For setting up the extrusion process two approaches are possible:-

1. The capacitance monitor is set to the mean value required, e.g. 50 pf/ft. (165 pf/metre). Extrusion conditions are then adjusted to obtain the required expansion characteristics.

2. A wire sample having cellular polyethylene of known specific gravity, e.g. 0.55 - 0.60, can be used to calibrate the capacitance monitor to the mean required.

Figure 2 illustrates the capacitance and diameter control possible during cellular extrusion.

In the absence of capacitance equipment some degree of extrusion control can be obtained by specific gravity measurement alone. Extrusion conditions are adjusted until a specific gravity of 0.55 - 0.60 is achieved in the insulation. A test method is described in Appendix I. Line control can be exercised by repeated measurements, and relating screw speed to line speed and the diameter of the insulated wire.

Conductor Preheat.

Conductor preheat is a well known technique for optimising the mechanical performance of solid extruded insulation(4). It is essential with cellular polyethylene insulation for telephone singles to develop an adequate elongation at break. Additionally conductor preheating assists adhesion of the insulation to the conductor. Conductors preheated to 85 - 95°C. are recommended and desirably obtained using induction preheaters which are capable of handling copper and aluminium. Minor adjustments within the advised temperature range can be used to regulate capacitance of the insulated wire. For this reason it is essential for the temperature to be precisely controlled.

TABLE I

Effect of conductor preheat on elongation of cellular insulation

	No Preheat	Preheat 90-95°C.
Elongation at break % BPO Specification M142A	30	450

0.5 mm (24 AWG) conductor, 0.2 mm (0.008"). cellular insulation thickness.

Extrusion Conditions

Extruder temperature profiles necessary to achieve a melt temperature 220 - 225°C. are given in Table 2. They should be adjusted by experimentation to optimise capacitance or specific gravity with the particular extruder and conductor size. Screw cooling may be necessary with extruders having a LD ratio between 16 and 20:1, to assist in obtaining the temperature needed. A minimum of filters (screens) is advised, e.g. 1 x 80 and 1 x 20 BS mesh screens. These serve primarily to filter any contaminants introduced through the hopper.

TABLE 2

Suggested extruder temperature profiles

Temperatures °C.	With screw cooling	No screw cooling
Barrel Rear Zone 1	150	140
Barrel Middle Zone 2	170	165
Barrel Middle Zone 3	220	195
Barrel Middle Zone 4	230	220
Head/Die	215	215
Screw Cooling water exit temperature.	20	-

Optimum extrusion conditions are best determined at the line speed intended and with conductor preheat applied as soon as practicable. With the basic temperature profile decided by experiment, the desired degree of expansion (capacitance/specific gravity) and outside diameter are obtained by minute adjustment of the front barrel zone temperature and line speed. The head/die controllers, which have little effect on melt temperature, should not be changed. It is not normally necessary to adjust the cooling water bath position set between 1 and 3 ft (0.3-1 metre) from the die.

Minor adjustments of wire preheat temperature regulate capacitance if necessary without changing the insulation diameter. A small gas jet flame applied to the front of the die prevents any problems with'drool' or material build-up around the die exit.

Melt temperature must always remain in control of the operator. Autogenous or adiabatic extrusion is not desirable as melt temperature may rise above 225°C. The problem can be corrected by the use of screw cooling water to lower the melt temperature until it is controlled by the applied heating.

Automatic control links can be adopted in cellular polyethylene insulation extrusion. Here the diameter gauge is linked to screw speed and the capacitance monitor to the front barrel zone temperature controller.

EXTRUSION OF COLOURED INSULATION

Coloured insulation is conveniently produced by dry tumbling the natural expandable compound with a small amount of colour masterbatch before extrusion. Pigments can interfere with the activation behaviour of the chemical blowing agent. To overcome this, and to compensate for the opacifying effect of cell formation, specially designed masterbatches are used. These minimise interaction between the pigments and blowing agent. Table 3 shows that with these systems excessive temperature adjustment is unnecessary between colours which can be regulated for capacitance by minor adjustment in the conductor preheat temperature and the front barrel zone setting.

TABLE 3

Example of alterations to extrusion conditions necessary with different colours

Colour	Barrel Front Zone temperature setting °C.	Conductor Preheat temperature setting °C.
White	229	85
Orange	229	85
Green	229	85
Red	227	85
Blue	231	90
Brown	231	90

Extruder $2\frac{1}{2}$ in. (60 mm), LD ratio 16:1, screw water cooled. Conductor diameter 0.625 mm (22 AWG) insulation wall thickness 0.25 mm (0.010".).

To maximise economy and maintain the extrusion conditions applied, colours can be changed on the run; i.e. without stopping to clean down the extruder. A colour change can be completed within two minutes by allowing the extruder hopper to empty before introducing the new colour.

TROUBLE SHOOTING

No difficulty in operation should occur by correctly applying the techniques reviewed above. As with most processes, problems do arise from time to time. To assist in speedy resolution, a trouble shooting guide is given in Appendix 2.

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APPENDIX I

Test for Determination of the specific gravity of a cellular polyethylene insulation on wire

The specific gravity of a cellular polyethylene insulation on wire is determined using the water displacement method. A balance weighing to 0.1 mg is used. To suspend the sample from the balance arm in water, a thin wire is needed which, to avoid confusion with the sample in the following descriptive procedure, is called a sinker.

Procedure:-

1. Weigh approximately 60 cm (2 ft) of the insulated wire in air and wrapped in a coil 5 cm (2 in) diameter. — Weight A.
2. Weigh the same sample plus the sinker in water. — Weight B.
3. Strip off the insulation and weigh the conductor in air. — Weight C.
4. Weigh the conductor plus the sinker in water. — Weight D.

Calculation

Weight of the insulation in air = A - C.

Excess of buoyancy above weight of insulation = D - B.

$$\text{Specific gravity of insulation} = \frac{A - C}{(A - C) + (D - B)}$$

The result is accurate to second significant figure, e.g. 0.55.

FIGURE I

THE EFFECT OF EXTRUSION MELT TEMPERATURE ON SPECIFIC GRAVITY AND CELL STRUCTURE OF CELLULAR POLYETHYLENE INSULATION.

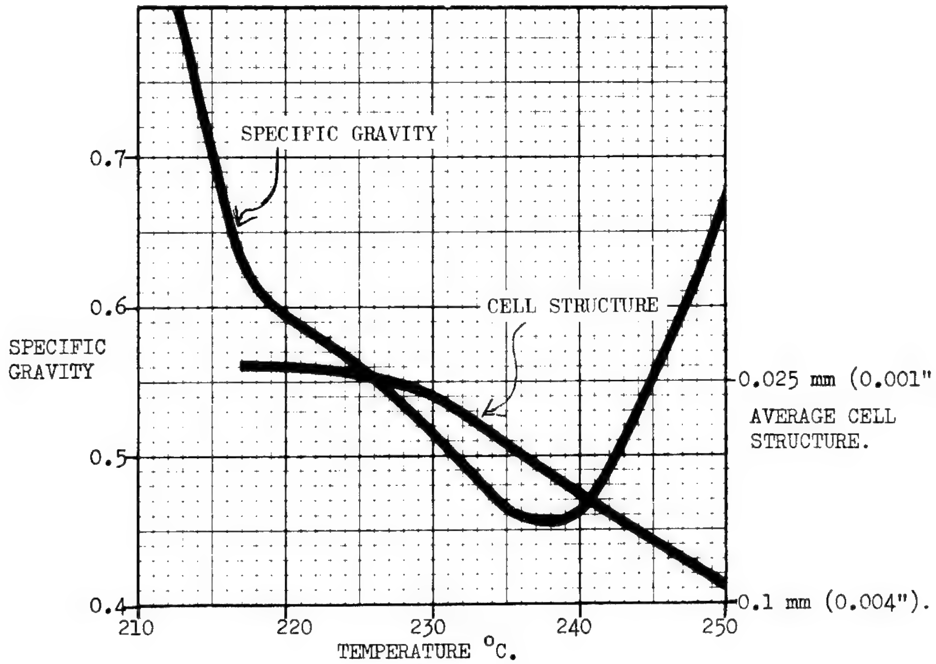
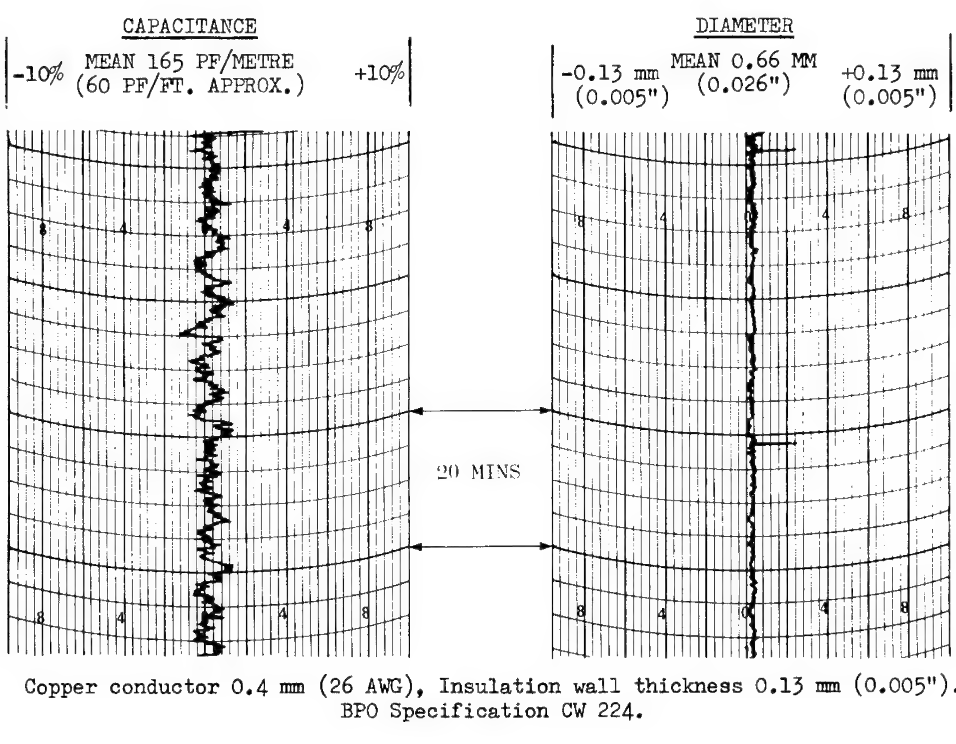


FIGURE 2

EXAMPLE OF CAPACITANCE AND DIAMETER CONTROL POSSIBLE WHEN EXTRUDING CELLULAR POLYETHYLENE INSULATION



Copper conductor 0.4 mm (26 AWG), Insulation wall thickness 0.13 mm (0.005").
BPO Specification CW 224.

APPENDIX 2

Trouble Shooting Guide. Extrusion of Cellular Insulation for Telephone Singles

Problem	Cause	Remedy
High capacitance or specific gravity.	1. Excessively high melt temperature, further increase worsens condition (accompanied by coarse irregular cell structure).	Reduce melt temperature to between 220-225°C. and optimise. This is the most common problem found.
	2. Melt temperature too low (cell structure normal).	Increase melt temperature to between 220 and 225°C. and optimise.
Low capacitance or specific gravity.	Melt temperature marginally too high.	Adjust to between 220-225°C. and optimise.
Outside diameter capacitance variations, (cyclic).	Mechanical 1. Screw speed varying.	Check and correct.
	2. Line speed varying.	Check and correct.
	Thermal 1. Inadequate temperature controllers or not working correctly.	Check and correct. Controllers must hold temperature to within 1°C.
	2. Conductor preheater cycling.	Check and correct.
Outside diameter/ capacitance variations, (non cyclic).	1. Screw cooling water varying.	Regulate water supply to screw.
	2. Autogenous extrusion.	Ensure melt temperature is being controlled by applied heaters. Reduce melt temperature if necessary by introducing or increasing screw cooling.
	3. Hopper bridging.	Ensure hopper cooling is working correctly.
Melt fracture.	High shear rate in die.	1. Use longer taper die. 2. Ensure suitable expandable compound is being used.
Unsatisfactory mechanical properties, low elongation at break.	Loss of conductor preheat.	Ensure conductor preheater operating correctly 85-95°C. and optimise.
Inadequate adhesion of insulation to conductor.	1. Dirty or oily conductor.	Clean conductor before entry to conductor preheater.
	2. Loss of conductor preheat.	Ensure conductor preheater operating correctly 85-95°C. and optimise.
	3. Specific gravity of insulation too low.	Reduce melt temperature to 220-225°C., optimise and adjust line speed.
Die drool	Lack of flame polish on die.	Correct by adopting small gas jet.
Elongated cell structure.	Die diameter too large.	Use correct diameter die. Approximate formula for calculation.

$$D_1 = \sqrt{\frac{D^2 + d^2}{1.6}}$$

where D_1 = die diameter.
D = OD of insulated conductor required.
d = conductor diameter required.

Problem	Cause	Remedy
Incorrect colour.	1. Wrong colour masterbatch being used.	Ensure correct colour masterbatch is being used.
	2. Very light pastel shade obtained (low capacitance/specific gravity). Melt temperature marginally high.	Adjust melt temperature until capacitance/specific gravity correct, 220-225°C. and optimise.
	3. Dark colour showing conductor (high capacitance/specific gravity). Melt temperature low or excessively high.	Adjust melt temperature until capacitance/specific gravity correct, 220-225°C. and optimise.
	4. Weak colour (correct capacitance/specific gravity).	Insufficient masterbatch. Ensure correct weighed amount, or flowmeter working correctly.

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COMPUTER CONTROLLED CABLE MEASUREMENTS

by

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Abstract

A Computer Operated Transmission Measuring Set, called COTMS, can quickly and accurately measure insertion loss and phase of two port devices over wide loss and frequency ranges. Appliques have been added to the basic COTMS for the purpose of characterizing telephone cables. Through the use of these appliques, a computer controlled pair selection switch, RLC bridge and loss range extender, cables can be consistently and extensively characterized in a small fraction of the time required by manual methods.

Introduction

Electrical measurements of cables have always presented many problems to the engineer. The large number of measurements involved with multipair cables, the time-consuming problem of pair selection and termination of unused pairs, the measurement capability required for high cross-talk loss and the ever widening frequency range required by modern communications are some of the difficulties. A measuring set that can automatically make a large number of high precision and high accuracy measurements is needed. A Computer Operated Transmission Measuring Set, COTMS, developed originally for network characterization, meets this need. This set, see Figure 1, has been designed to quickly and accurately measure insertion loss and phase to within a requested precision. The best precision allowed is .0005 dB for loss. However as the loss of the unknown increases more measurements must be averaged to obtain the requested precision. The total measurement time will vary according to the number of measurements that are averaged. To increase the measurement speed a variable precision may be used. This variable precision is dependent on the loss of the unknown; the larger the loss the less stringent the precision becomes.[1]

The resolution of COTMS is .001 dB for loss and .01 degrees for phase. Phase measurements are usually modulus 360 degrees, however modulus 180 degrees is available.

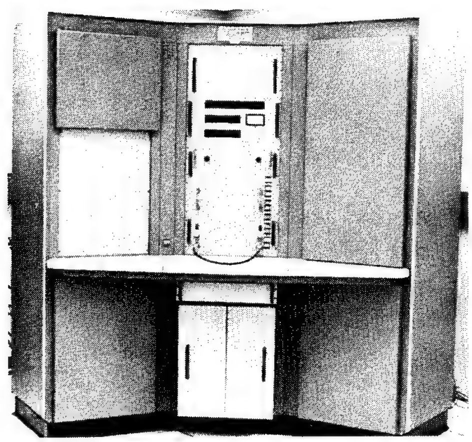

Figure 1. COTMS (Computer Operated Transmission Measuring Set).

Loss and Phase Measurements Using the Comparison Method

The comparison method at an intermediate frequency is used to determine the loss and phase of the unknown, Figure 2. A local oscillator provides the proper frequency to the reference and measurement paths for converting the test signal to a fixed intermediate frequency of 27.777 KHz. The unknown and standard paths are rapidly interchanged between the signal source and the loss detector, while the loss standard is adjusted to have a loss equal to that of the unknown. The difference in phase of the standard and unknown paths also provides the phase of the unknown, since the phase shift of the loss standard and IF strap are equal.

When the loss of the unknown exceeds 40dB, a 40 dB pad is inserted into the

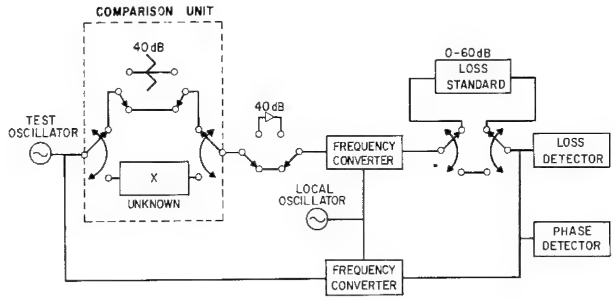

Figure 2. Comparison method used to determine the loss and phase of the unknown "X".

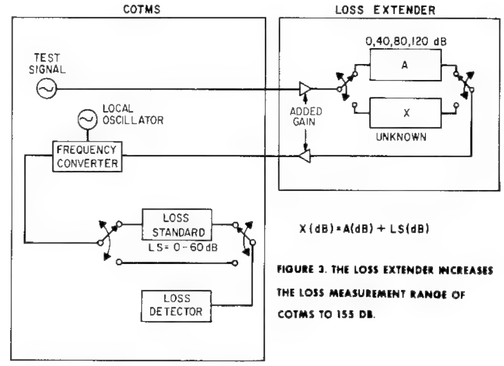

FIGURE 3. THE LOSS EXTENDER INCREASES THE LOSS MEASUREMENT RANGE OF COTMS TO 155 DB.

standard path, and at the same time a 40 dB amplifier is placed in the measurement path. This helps to reduce internal crosstalk in the comparison switches, while also improving the system noise figure by about 20 dB.[2] However, since this pad has its own frequency characteristics, another comparison cycle measuring the difference in the 40 dB pad and standard strap is made every time the pad is used. The switching of relays and control of all other components in COTMS is performed by the computer, a Digital Equipment Corporation PDP-9. Speeds up to five complete measurements a second have been reached.

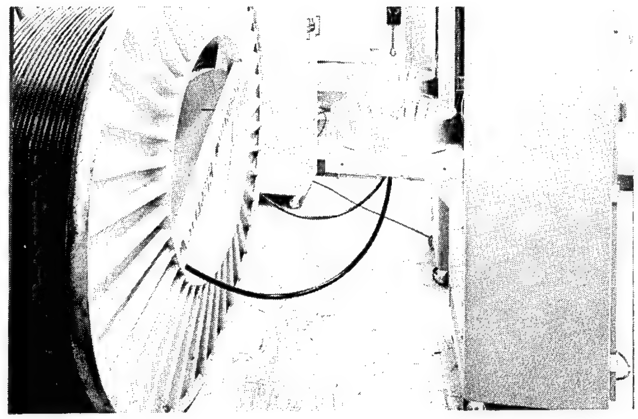

Figure 4. The pair switch is able to choose any pair or two pair combination from a maximum of 52 pairs.

Frequency and Loss Range Capabilities

A series of frequency multipliers are used to obtain a frequency range of 50 Hz to 1 GHz. Below 50 MHz frequencies are set within a precision of .01 Hz in 1 millisecond of being signaled. Above 50 MHz a frequency is set to a precision ranging from .02 to .08 Hz within 10 milliseconds.[3]

The original loss range capability of COTMS, -40 dB to 100 dB, accomodates most coaxial and multipair cable measurement needs. However, crosstalk loss in multipair cables is frequently higher than 100 dB, therefore a computer controlled loss range extender was designed as an applique to COTMS. This extender replaces the function of the comparison unit in COTMS and provides the added gain needed to measure losses up to 155 dB, Figure 3. At present the loss-frequency characteristics of the amplifiers and transformers used in the loss extender limit its use to between 100 KHz and 15 MHz. A repeatability of 0.1 dB for loss and 1.0 degree for phase is attainable at the 150 dB level, while below 120 dB the repeatability is improved to 0.005 dB and 0.1 degrees.[4]

Computer Controlled Pair Selection Switch

Even with all the speed of a computer controlled measuring set, multipair cable measurements still require large amounts of time. This time is largely spent in the manual connection of each cable pair to the test set. To reduce this time consuming problem, a 52 pair computer controlled selection switch was designed using miniature spring relays. These relays are used in a relay-tree configuration and are contained in two separate cabinets, one for each end of the cable, see Figure 4. This switch has the ability to choose any two pair combination within 20 milliseconds after being signaled by the computer. All unused pairs can be terminated,

opened or grounded, and an isolation of at least 140 dB at 3 MHz exists between any two signal paths within a cabinet.[5] Insertion loss, phase and crosstalk measurements of all pairs connected to the pair switch can be automatically and quickly made.

Each cabinet is able to simultaneously send and detect; thus near-end as well as far-end crosstalk can be measured using the pair switch, Figure 5. For crosstalk measurements the switch, under instructions from the computer, connects a two pair combination to the loss extender and terminates all other pairs approximately in their characteristic impedance. With the send and detect pairs chosen, the test signal is sent down the disturbing pair and the crosstalk loss on the disturbed pair is measured. After this measurement is completed, a new frequency is set or another pair combination is chosen. This procedure continues until all measurements are made. A fifty pair cable, for instance, measured for far-end crosstalk at five frequencies for all combinations (1225 per frequency) would require a running time of approximately 1-1/2 hours.

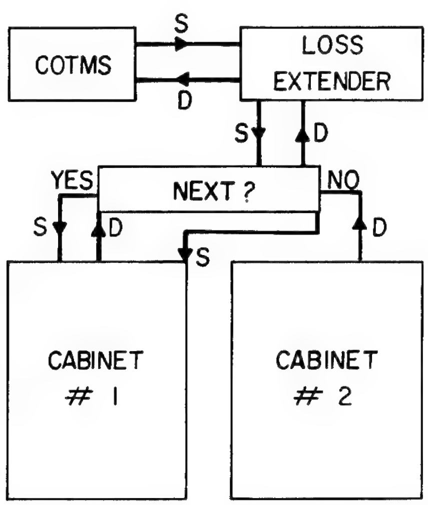

Figure 5. The pair switch is capable of measuring near-end as well as far-end crosstalk.

RLC Measurements

As stated earlier, the pair switch was designed with the ability to open or ground unused pairs. A General Radio automatic 1 KHz RLC bridge was modified to operate in conjunction with the pair switch for RLC measurements.[6] The switch presents to the bridge a two pair combination requested by the computer, at the same time properly grounding or opening unused pairs. The RLC bridge is then able to manipulate these four conductors and ground to make resistance, inductance and capacitance measurements. The following 1 KHz measurements can be automatically made on any pairs connected to the pair switch:

Inductance:	Loop
Resistance:	Loop and individual conductors.
Capacitance:	The three direct capacitances of a pair and all ten direct capacitances of a two pair combination.

With the placement of a tee between the send and detect ports of COTMS, terminal impedance measurements can be made. This impedance can be found by measuring the loading effects on the transmission through the tee for the following conditions: (1) an open tee, (2) a tee terminated in an impedance standard, and (3) the tee terminated in the unknown impedance.

Processing Measured Data

To expedite the input and output of information to and from the computer, a

Figure 6. Peripherals associated with the COTMS.

line printer, disk, three tape drives, two X-Y recorders and teletypewriter are all part of the COTMS system, see Figure 6. The computer not only controls COTMS and its appliques, but records and processes the data COTMS measures. Since all measured data is recorded, the processing of data can take place during the measurement run or at some later time. As an example, pair to pair crosstalk readings are frequently statistically summarized as follows:

ALL XT IN DB/1KFT

	MEAN	MINIMUM	MAXIMUM	RMS	SIGMA
PAIR TO PAIR	*	*	*	*	*
POWER SUMS †	*	*	*	*	*
INSERTION LOSS	*	*	*	*	*

50 WORST PAIR TO PAIR READINGS

SEND PAIR	RECEIVE PAIR	XT DB/1KFT
*	*	*
*	*	*
*	*	*

POWER SUM VALUES

PAIR	DB/1KFT
*	*
*	*

With this information, along with complete listings of all crosstalk pair combinations, cables can be studied for crosstalk characterization in great detail.

Measurements of insertion loss and insertion phase are also processed by the computer to yield the primary and secondary cable constants. The following is a standard output format available for cable constants as a function of frequency:

ALL VALUES PER MILE

FREQ.	ALPHA	ALPHA/$\sqrt{F}$	INDUCTANCE	CAPACITANCE	Zo(Ω)
*	*	*	*	*	*
*	*	*	*	*	*
*	*	*	*	*	*
FREQ.	BETA	DELAY	RESISTANCE	RES./$\sqrt{F}$	Zo($\angle$)
*	*	*	*	*	*
*	*	*	*	*	*
*	*	*	*	*	*

The primary and secondary cable constants are determined from insertion loss and insertion phase using one of the following two methods:

Method 1.[7]

A. The mutual capacitance and dissipation factor of the pair being measured must be known.

B. Measure the insertion loss and insertion phase of the pair between known terminations.

C. Correct the insertion loss and insertion phase to the true loss and phase of the pair by determining the loss or gain due to mismatches. The propagation constant, γ, is now known.

$$\gamma = \alpha + j\beta = \sqrt{R+j\omega L}\,\sqrt{G+j\omega C}$$

D. Using the fact that:

dissipation factor $\approx G/(\omega C)$

"G" can be found.

E. And because:

$$\sqrt{R+j\omega L} = \gamma/\sqrt{G+j\omega C}$$

"R" and "L" can be computed.

F. And finally:

$$Zo = \sqrt{R+j\omega L} \;/\; \sqrt{G+j\omega C}$$

Method 2.[8]

A. Measure the input impedance of a pair terminated in an impedance standard "Zs".

† Power sums = Approximate value of the power expected on the detect pair if the oscillator signal were applied to all pairs in the cable simultaneously.

$$Z(IN)=\left[\frac{(Zs+Zo)\exp(\gamma\ell)+(Zs-Zo)\exp(-\gamma\ell)}{(Zs+Zo)\exp(\gamma\ell)-(Zs-Zo)\exp(-\gamma\ell)}\right]*Zo \qquad (1)$$

The above equation, equation (1), expresses the input impedance, Z(IN), in terms of the characteristic impedance of the pair, Zo, the impedance standard, Zs, the length of the pair, ℓ, and the propagation constant γ.

where $\gamma = \alpha + j\beta$

$$= \sqrt{R + j\omega L}\,\sqrt{G + j\omega C}$$

B. Measure the insertion loss and insertion phase of the pair and correct these values to obtain the true attenuation and phase shift. Therefore:

$\gamma = \alpha + j\beta$ is known. Zo can now be found by equation (1).

C. And finally:

$$R + j\omega L = Zo \cdot \gamma$$

$$G + j\omega C = \gamma/Zo$$

The cable constants are again found.

The loop resistance and the direct capacitance values measured by the RLC bridge are also processed by the computer into the following quantities:

RESISTANCE: Unbalance

CAPACITANCE: Mutual

Unbalance to ground

Pair to pair unbalance.

Conclusion

A Computer Operated Transmission Measuring Set, COTMS, has been designed to quickly and accurately measure insertion loss and phase of two port devices. A computer controlled pair selection switch, RLC bridge and loss range extender have been added to COTMS for the purpose of measuring cables. COTMS and its appliques form a "stand alone" system, since they are able to measure, process and output cable parameters. With the speed and capabilities of the COTMS system, cables can be electrically characterized in a fraction of the time required by manual methods.

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REGRESSION ANALYSIS OF COMPUTER MEASUREMENTS
OF HIGH FREQUENCY COAX LOSS AND DELAY

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ABSTRACT

The attenuation, α, and phase delay, τ, of 0.375" coax with a 0.012" thick outer conductor can be accurately approximated above 1.0 MHz by

$$\alpha = \text{ALOSS } (1 + \frac{.0062}{\sqrt{f}})\sqrt{f} + \text{BLOSS } f$$

$$\tau = \text{ATAU} + \text{BTAU}/\sqrt{f}$$

where f is frequency in MHz. A Computer Operated Transmission Measuring Set (COTMS) technique is presented for least-squares fitting measured loss and delay to these equations. This yields estimates of the above parameters together with the fit variances. The net result is a new way to specify coax transmission response plus a fast, computerized method to measure it.

INTRODUCTION

In 1945 Western Electric first started producing 0.375" (953 mm) coaxial cable. Since its initial installation with an L-1 carrier system, successive generations of transmission systems have further utilized it by adding more channels at higher frequencies. Each new system has required more and better knowledge of the coax's characteristics. Today this process has brought us to the need for more numerous, more accurate and high frequency transmission tests than ever before. Moreover, the quantity of measurements this involves requires new, statistical methods for processing it.

With the development of COTMS, (Computer Operated Transmission Measuring Set), our need is met for not only speed, accuracy and bandwidth but also, for the first time, the capability of fast data analysis is provided. This ability has brought about a new method for measuring, analyzing and talking about the coax's transmission response. This method is based upon two parametric equations which accurately approximate the loss and phase delay of the coax and a curve fitting technique that allows COTMS to measure the coax and estimate the parameters in the two equations.

The result is that we can measure a coax, reduce its nominal response to four parameters and compare these to specifications in about one minute. Then, because we can measure a large number of cables conveniently, we can gather long term statistics, study variances, etc.

This paper describes the theory behind the parametric equations and curve fitting techniques, describes their normal use, and presents some sample results.

PARAMETRIC EQUATIONS

It is shown in the Appendix that the attenuation, α, and phase delay, τ, of a coax with electrically thick conductors can be approximated by the parametric equations:

$$\alpha = \text{ALOSS } \sqrt{f} + \text{BLOSS } f + \text{CLOSS} \quad (1)$$

$$\tau = \text{ATAU} + \text{BTAU}/\sqrt{f} \quad (2)$$

where the coefficients ALOSS, BLOSS, CLOSS and ATAU, BTAU are, as shown in the Appendix, frequency independent functions of the coax's mechanical parameter, i.e. diameters, conductivities and dielectric properties.

Since Eqs. (1) and (2) are derived by a long series of approximations, we shall indicate their accuracy by comparing them to the loss and phase delay calculated by a very accurate computer program. This program, called CORM4, computes the modified Bessel functions,[1] then calculates the exact resistances and inductances of the lines, and from this it finds the attenuation and delay. Table I compares this program to Eqs. (1) and (2) for some assumed mechanical parameters which are fairly typical of 0.375" serrated seam coax.

TABLE I

COMPARISON OF COMPUTER CALCULATED TRANSMISSION RESPONSE TO EQUATIONS (1) AND (2) FOR ASSUMED MECHANICAL PARAMETERS.

	CALCULATED ATTENUATION			CALCULATED PHASE DELAY		
FREQUENCY (MHz)	COMPUTER (dB/MILE)	EQ. (1) (dB/MILE)	ERROR RATIO (PPM)	COMPUTER (μSEC/MILE)	EQ. (2) (μSEC/MILE)	ERROR RATIO (PPM)
0.5	2.7303	2.7267	1327	5.714810	5.714845	6
1.0	2.8489	2.8478	286	5.685825	5.685853	5
2.0	5.4356	5.4356	174	5.665342	5.665352	2
5.0	8.5885	8.5878	75	5.647158	5.647161	1
10.0	12.1494	12.1489	42	5.637991	5.637993	.4
50.0	27.2644	12.2641	12	5.625757	5.625757	.2
100.0	38.6825	38.6823	5	5.622858	5.625858	.1

COEFFICIENTS OF EQUATIONS (1) AND (2)

ALOSS = 3.8199 dB/(mile $\sqrt{\text{MHz}}$) ATAU = 5.615859 μsec/mile

BLOSS = 0.0046 dB/(mile MHz) BTAU = .069994 μsec$\sqrt{\text{MHz}}$/mile

CLOSS = 0.0233 dB/mile

ASSUMED MECHANICAL PARAMETERS

$g_o = g_i = 6.00015 \quad 10^5$ mhos/cm

D = .3686 inches PF = 30 μ radians

d = .1003 inches $\varepsilon_r = 1.0944$

t = .0100 inches ($T = 55^{\circ}F$)

It shows that, for this coax, Eq. (1) is accurate above 1 MHz with an error that decreases from less than 300 ppm at 1 MHz to 5 ppm at 100 MHz. It also shows that Eq. (2) is very accurate in predicting theoretical phase delay since its error ratio is less than 5 ppm for frequencies above 1 MHz.

Our objective is to curve fit Eqs. (1) and (2) to measured data and estimate coefficients. This would be simplified if we could reduce Eq. (1) to a two parameter equation instead of three. We will do this by numerically evaluating the ratio of CLOSS to ALOSS for all conceivable variations in the coax's mechanical parameters. Let us assume that the diameters and conductivities are within the following ranges:

$$.366'' \leq D \leq .372''$$

$$.1001'' \leq d \leq .1005''$$

$$5.54 \leq g_i \leq 6.45 \quad 10^5 \text{ mhos/cm}$$

$$5.54 \leq g_o \leq 6.45 \quad 10^5 \text{ mhos/cm}$$

Now if each of these parameters is allowed to vary in the above range while the rest are set at their median value then it can be shown that

$$.0061 \leq \frac{\text{CLOSS}}{\text{ALOSS}} \leq .0063$$

where the units of $\frac{\text{CLOSS}}{\text{ALOSS}}$ are $\sqrt{\text{MHz}}$. So if we define this ratio to be 0.0062 then Eq. (1) becomes

$$\alpha \doteq \text{ALOSS} \left(1 + \frac{.0062}{\sqrt{f_{\text{MHz}}}}\right) \sqrt{f} + \text{BLOSS } f \tag{3}$$

and this new equation will differ from the original by at most 100 ppm at 1 MHz.

CURVE FITTING

We have established that Eqs. (2) and (3) can accurately calculate the transmission response of our coax above 1 MHz

The problem now is to measure any one particular coax and estimate the parameters in the two equations.

Let us consider first the attenuation equation, Eq. (3). We know that if the attenuation is measured at any frequency, f_i, the measured value will probably differ from the actual value due to random noise, nonuniformities in the coax, semi-random testing errors, etc. Let us assume then, that the measured attenuation is a random variable, α_i, given by the equation

$$\alpha_i = \text{ALOSS}\ (1 + \frac{.0062}{\sqrt{f_i}})\ \sqrt{f_i} + \text{BLOSS}\ f_i + e_i \tag{4}$$

where e_i is a zero mean, Gaussian, random variable whose variance is a fixed but unknown quantity, σ^2,

$$E\ (e_i{}^2) = \sigma^2 \tag{5}$$

Now we will measure the loss at N frequencies and from the N values of α_i we wish to find the quantities a and b which are the Best Linear Unbiased Estimates of ALOSS and BLOSS. That is, a and b are random variables whose expected values are ALOSS and BLOSS and whose variances are minimum. This problem is solved by defining the functions

$$w_i = (1 + \frac{.0062}{\sqrt{f_i}})^2\ f_i$$

$$x_i = \frac{f_i}{\sqrt{w_i}}$$

$$y_i = \frac{\alpha_i}{\sqrt{w_i}}$$

Now Eq. (4) can be written

$$y_i = \text{ALOSS} + \text{BLOSS}\ x_i + \frac{e_i}{\sqrt{w_i}}$$

But this is a linear least-squares estimation problem with a weighted variance. Its solution is[2]

$$b = \frac{\Sigma w_i (x_i - \bar{x}) y_i}{\Sigma w_i (x_i - \bar{x})^2}$$

and

$$a = \bar{y} - b\bar{x}$$

where

$$\bar{y} = \frac{\Sigma w_i y_i}{\Sigma w_i};\ \bar{x} = \frac{\Sigma w_i x_i}{\Sigma w_i}$$

Also the error variance, σ^2, in Eq. (5) can be estimated by the quantity S^2 as follows:

$$S^2 = \frac{\Sigma w_i (y_i - a - bx_i)^2}{N - 2} \tag{6}$$

In a similar manner to the above we can assume that the measured phase delay, τ_i, is found by

$$\tau_i = \text{ATAU} + \text{BTAU}/\sqrt{f_i} + e_i$$

where the variance of e_i is the unknown constant $\sigma_\tau{}^2$ multiplied by the function $g^2(f)$

$$E(e_i{}^2) = \sigma_\tau{}^2\ g^2\ (f_i) \tag{7}$$

The weighting function of g(f) is introduced to enable us to correct for the fact that phase delay is not measured with equal precisions at different frequencies.

Now by defining the functions

$$w_i = \frac{1}{g(f_i)} \qquad x_i = 1/\sqrt{f_i} \qquad y_i = \tau_i \tag{8}$$

we can estimate ATAU and BTAU using the same equations above.

TYPICAL TEST PROCEDURE

In general the coax is measured at 50 to 100 frequencies up to 100 MHz. These frequencies are usually chosen in a square root manner according to the formula

$$f_i = \left[\sqrt{f_{low}} + (\sqrt{f_{hi}} - \sqrt{f_{low}})\frac{i-1}{N-1}\right]^2$$

where N is the number of measurements and f_{hi} and f_{low} are the highest and lost frequencies in the sweep.

After the effects of the connecting leads are subtracted, the phase delay is calculated from the measured phase, θ, by

the formula

$$\tau = \frac{(360^{\circ})M + \theta^{\circ}}{(360^{\circ})f} \qquad (9)$$

Since COTMS measures phase between 0° and 360°, the quantity $(360^{\circ})M$, (M is an integer), must be added in order to find the entire phase shift of the cable. M is calculated in a bootstrap manner in which the phase is first measured at low frequencies where M is zero. From these measurements an ATAU and BTAU can be roughly calculated which allows phase to be estimated at a higher frequency from Equations (2) and (9). The phase is then measured at this higher frequency and M is adjusted to bring the estimated phase close to the measured phase. This process can be repeated until the entire frequency band is covered.

Once tau is found we only need to know the weighting in Eq. (8) to utilize the curve fitting procedure. This is found by assuming the COTMS measures phase at every frequency with equal variance. Since this is a fairly good assumption it follows from Eq. (9) that the variance for the measured tau points is

$$E\ (\tau - \bar{\tau})^2 = \frac{E\ (\theta - \bar{\theta})^2}{(360\ f)^2} \qquad (10)$$

consequently we have the tau weighting from Eqs. (7) and (8)

$$w_i = 360\ f_i$$

and the curve fitting procedure above can now be implemented.

After tau is fit, we next process the attenuation data. First, we use the ATAU estimate, Equation (A-8), which shows ATAU = $\sqrt{\mu\varepsilon}$, and assumed values of μ and ε, to estimate length. This is divided into the loss measurements to give attentuation per mile, since insertion loss effects are negligible. This loss per mile is then curve fit.

We assumed in Eq. (5) that COTMS measures loss with equal variance so there is no additional weighting to calculate. Although this assumption is not too accurate, a realistic weighting is cumbersome to implement and does not affect the final answers substantially.

Finally, since ALOSS changes with temperature, we normally calculate its value at 55°F by reducing it by 0.11% for each degree over 55°F. Also, because power factor is more familiar to people than BLOSS, we usually assume a μ and ε and estimate power factor from Eq. (A-5) which shows

$$\text{BLOSS} = \frac{\sqrt{\mu\varepsilon}}{2}\ \text{PF}$$

TYPICAL TEST RESULTS

In order to illustrate the preceding sections, we will present the test results for a typical unit of coax. For this test we measured a 1521 foot length using 98 frequencies which were chosen in a square root manner between 0.09 MHz and 100 MHz. The phase delay was calculated from the phase measurements and tau was then curve fit at all frequencies above 1 MHz. The estimated fit parameters were:

$$\text{ATAU} = 1.618518\ \mu\ \text{sec}$$

$$\text{BTAU} = .020792\ \mu\ \text{sec}\ \sqrt{\text{MHz}}$$

$$\text{STD DEV} = .079\quad \text{degrees}$$

and, as shown in Figure (1), the fit curve was extremely close to the measured data. From ATAU, an estimated ε_r of 1.0944 and μ_r of 1, we can estimate the length to be 1521.7 feet. From BTAU and Eq. (A-9), which shows BTAU = ALOSS/2π, we can estimate the ALOSS we should get at 55°F to be 3.857 dB/(mile $\sqrt{\text{MHz}}$). Also we can use the standard deviation as a measure of the closeness of the fit curve to the measurements. That is, from Eq. (10) and the above sigma, we can find the standard deviation around the fit curve to be

$$\sigma_\tau = \frac{.00022}{f_{\text{MHz}}}\ \mu\ \text{sec} \qquad (11)$$

So, since the difference between the fit and the measured delay points is approximately Gaussian distributed, this difference should be less than twice Eq. (11) about 95% of the time.

Next we analyzed the loss data and found

$$\text{ALOSS} = 3.834\ \text{dB/ (Mile}\ \sqrt{\text{MHz}})$$

$$\text{BLOSS} = .0045\ \text{dB/ (Mile MHz)}$$

$$\text{STD DEV} = .0061\ \text{dB/ (Mile}\ \sqrt{\text{MHz}})$$

Figure (2) shows that the measured loss points matched the fit values fairly well. The ALOSS term, which is corrected to 55°F is within 0.9% of the value predicted from BTAU and this is a reasonably close agreement. We can use our estimation of BLOSS,

Eq. (A-5), and an assumed ε_r of 1.0944 to estimate the power factor to be about 29 μ radians, and finally as was done above, we can use the standard deviation as a measure of the closeness of fit.

SUMMARY

The above procedure allows COTMS to measure the loss and phase of a coax and extract the coefficients of the attenuation and delay equations. From these one can estimate the cable lenth, the power factor and the square root of frequency component of loss. Because these parameters can be quickly calculated, we can measure a large proportion of production cables. This allows us to compare them to specifications, calculate statistics and, consequently, determine the nominal transmission response more accurately than ever before.

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APPENDIX

DERIVATION OF ATTENUATION AND DELAY EQUATIONS

In 1934, S. A. Schelkunoff derived the equations for the surface impedance of a cylindrical conductor.[1] He showed that the surface impedance for a solid wire of diameter, d, can be approximated by

(A-1)

$$Z_{inner} = \frac{1}{d}\sqrt{\frac{\mu f}{\pi g_i}}\,(1 + j) + \frac{1}{\pi g_i d^2}$$

where

f is frequency

μ is the permeability of the conductor

g_i is the conductivity of the conductor

j is $\sqrt{-1}$

He also showed that the exact equation for the inner surface impedance of a coax's outer conductor is

(A-2)

$$Z_{outer} = \frac{(1+j)}{D}\sqrt{\frac{\mu f}{\pi g_o}}\,\frac{K_o(\sigma a)I_1(\sigma b) + I_o(\sigma a)K_1(\sigma b)}{I_1(\sigma b)K_1(\sigma a) - I_1(\sigma a)K_1(\sigma b)}$$

where

a and b are the inner and outer radii of the cylinder

D is the diameter which equals 2a

σ is $(1+j)\sqrt{\pi f \mu g_o}$

g_o is the outer conductor conductivity

I_o, I_1, K_o and K_1 are the first modified Bessel functions of the first and second kind.

In order to simplify Eq. (A-2) we us the following asymptotic approximations for the Bessel functions·

$$I_o(u) \cong \frac{e^u}{\sqrt{2\pi u}}\left(1 + \frac{1}{8u}\right)$$

$$I_1(u) \cong \frac{e^u}{\sqrt{2\pi u}}\left(1 - \frac{3}{8u}\right)$$

$$K_o(u) \cong \sqrt{\frac{\pi}{2u}}\,e^{-u}\left(1 - \frac{1}{8u}\right)$$

$$K_1(u) \cong \sqrt{\frac{\pi}{2u}}\,e^{-u}\left(1 + \frac{3}{8u}\right)$$

When these are substituted we obtain

(A-3)

$$Z_{outer} = \frac{(1+j)}{D}\sqrt{\frac{\mu f}{\pi g_o}}\;\frac{(1-\frac{1}{8\sigma a})(1-\frac{3}{8\sigma b})+e^{-2\sigma(b-a)}(1+\frac{1}{8\sigma a})(1+\frac{3}{8\sigma b})}{(1-\frac{3}{8\sigma b})(1+\frac{3}{8\sigma a})-e^{-2\sigma(b-a)}(1-\frac{3}{8\sigma a})(1+\frac{3}{8\sigma b})}$$

At high frequencies the conductor is electrically thick and the product of σ and the thickness, b-a, will be large. In this case the exponentials will be close

to zero and we have

$$Z\ \text{outer} \cong \frac{1+j}{D}\sqrt{\frac{\mu f}{\pi g_o}}\ \frac{\left(1-\frac{1}{8\sigma a}\right)}{\left(1+\frac{3}{8\sigma a}\right)}$$

Since the quantitity $\frac{3}{8\sigma a}$ is also small we can use the approximation

$$(1+X)^{-1} \simeq 1 - X;\ |X| \ll 1$$

for the denominator and obtain (after multiplying and substituting for σa)

$$Z_{\text{outer}} \cong \frac{(1+j)}{D}\sqrt{\frac{\mu f}{\pi g_o}} - \frac{1}{\pi g_o D^2}$$

This result is more accurate than the one in Schelkunoff since he apparently ignored the denominator of Eq. (A-2). Using the results of Eqs. (A-1) and (A-3) we can calculate the entire resistance of the coax as the sum of the real parts of Z_{inner} and Z_{outer}.

$$R = \sqrt{\frac{\mu f}{\pi}}\left(\frac{1}{\sqrt{g_i}\,d} + \frac{1}{\sqrt{g_o}\,D}\right) + \frac{1}{\pi}\left(\frac{1}{g_i d^2} - \frac{1}{g_o D^2}\right)$$

Likewise the entire inductance is the sum of the space inductance and the conductor inductances

$$L = L_{\text{space}} + L_{\text{inner}} + L_{\text{outer}}$$

$$= \frac{\mu}{2\pi}\ln\frac{D}{d} + \frac{1}{2\pi}\sqrt{\frac{\mu}{\pi}}\left(\frac{1}{\sqrt{g_i}\,d} + \frac{1}{\sqrt{g_o}\,D}\right)\frac{1}{\sqrt{f}}$$

for convenience we now define the quantities a_o, a_1, b_o, and b_1

$$a_o = \frac{1}{\pi}\left(\frac{1}{g_i d^2} - \frac{1}{g_o D^2}\right)$$

$$a_1 = \sqrt{\frac{\mu}{\pi}}\left(\frac{1}{\sqrt{g_i}\,d} + \frac{1}{\sqrt{g_o}\,D}\right)$$

$$b_o = \frac{\mu}{2\pi}\ln\frac{D}{d}$$

$$b_1 = \frac{a_1}{2\pi}$$

so that R and L can be written

$$R = a_o + a_1\sqrt{f}$$

$$L = b_o + b_1/\sqrt{f}$$

Now to derive the parametric attenuation equation we substitute for R and L in the approximation

$$\alpha \cong \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}}$$

where G and C are the conductance and capacitance. This yields

$$\alpha \cong \frac{1}{2}\sqrt{\frac{C}{b_o}}\ \frac{a_o + a_1\sqrt{f}}{\sqrt{1+\frac{b_1}{b_o\sqrt{f}}}} + \frac{G}{2}\sqrt{\frac{b_o}{C}}$$

Since the ratio of b_1/b_o is small we can use the approximation

$$(1+X)^{-1/2} \cong 1 - \frac{X}{2};\ |X| \ll 1$$

to yeild

$$\alpha \cong \frac{1}{2}\sqrt{\frac{C}{b_o}}\ (a_o + a_1\sqrt{f})\left(1 - \frac{b_1}{2b_o\sqrt{f}}\right) + \frac{G}{2}\sqrt{\frac{b_o}{C}}$$

$$\cong \frac{1}{2}\sqrt{\frac{C}{b_o}}\left[a_1\sqrt{f} + \left(a_o - \frac{a_1 b_1}{2b_o}\right)\right] + \frac{G}{2}\sqrt{\frac{b_o}{C}}$$

We have neglected the term $\frac{a_o b_1}{2b_o\sqrt{f}}$ because it is small by itself and also because previous terms containing $1/\sqrt{f}$ have been neglected. (If all the above approximations are expanded to calculate the entire $1/\sqrt{f}$ component it would be seen that the entire component is also small enough to ignore.)

We can now use the knowledge that the conductance, G, increases approximately proportional to frequency, so the ratio of $\frac{G}{\omega C}$, which equals the power factor, PF, is

a constant. It therefore follows that the attenuation can be expressed by

$$\alpha = \text{ALOSS} \sqrt{f} + \text{BLOSS } f + \text{CLOSS}$$

where ALOSS, BLOSS, CLOSS are defined by

$$\text{ALOSS} = \frac{1}{2} \sqrt{\frac{C}{b_o}}\, a_1$$

$$= \frac{\sqrt{\pi\varepsilon}}{\ln\frac{D}{d}} \left(\frac{1}{\sqrt{g_i}\,d} + \frac{1}{\sqrt{g_o}\,D}\right) \qquad \text{(A-4)}$$

$$\text{BLOSS} = \frac{1}{2} \sqrt{b_o C}\ \text{PF}$$

$$= \frac{\sqrt{\mu\varepsilon}}{2}\ \text{PF} \qquad \text{(A-5)}$$

$$\text{CLOSS} = \text{ALOSS} \left(\frac{a_o}{a_1} - \frac{b_1}{2b_o}\right) \qquad \text{(A-6)}$$

$$= \frac{\text{ALOSS}}{\sqrt{\mu\pi}} \left[\frac{1}{\sqrt{g_i}\,d} - \frac{1}{\sqrt{g_o}\,D} - \frac{1}{2\ln\frac{D}{d}} \left(\frac{1}{\sqrt{g_i}\,d} + \frac{1}{\sqrt{g_o}\,D}\right)\right]$$

In a similar development we calculate the phase of the coax. Starting with the approximation:

$$\beta \cong \omega \sqrt{LC}\, \left[1 - \frac{1}{8} \left(\frac{R}{\omega L}\right)^2\right]$$

we substitute for R and L to obtain

$$\beta = \omega \sqrt{b_o C} \sqrt{1 + \frac{b_1}{b_o\sqrt{f}}} \left[1 - \frac{1}{8} \left(\frac{a_1}{2\pi b_o}\right)^2 \frac{1}{f}\right]$$

When we use the approximation:

$$\sqrt{1 + X} \cong 1 + \frac{1}{2}X + \frac{1}{8}X^2 \ ; \quad |X| < 1$$

plus the fact that $a_1 = 2\pi b_1$ we obtain

$$\beta \cong \omega\sqrt{b_o C} \left[1 + \frac{1}{2} \frac{b_1}{b_o} \frac{1}{\sqrt{f}}\right] \qquad \text{(A-7)}$$

We wish to calculate the phase delay, τ, which is defined as β divided by ω. It follows from Eq. (A-7) that τ can be expressed as

$$\tau = \text{ATAU} + \text{BTAU}/\sqrt{f}$$

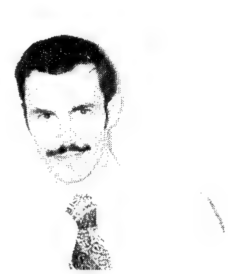
where ATAU and BTAU are defined to be.

$$\text{ATAU} = \sqrt{b_o C}$$

$$= \sqrt{\mu\varepsilon} \qquad \text{(A-8)}$$

$$\text{BTAU} = \frac{\sqrt{b_o C}}{2} \frac{b_1}{b_o}$$

$$= \frac{\text{ALOSS}}{2\pi} \qquad \text{(A-9)}$$



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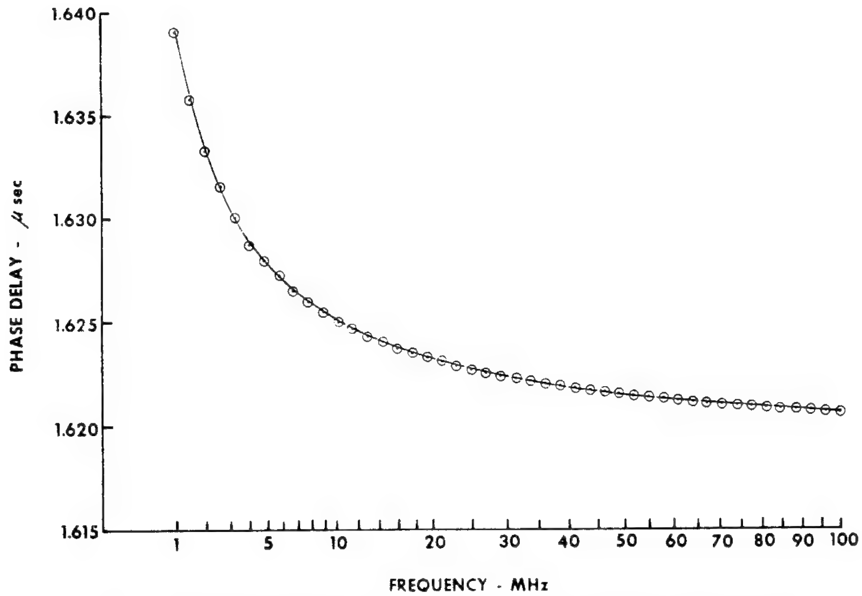

FIG. 1 - COMPARASION OF MEASURED AND FIT PHASE DELAY FOR TYPICAL COAX. CIRCLED POINTS ARE MEASURED VALUES. SOLID LINE IS FIT CURVE. EQUATION FOR FIT CURVE IS

$$\tau = 1.618518 + .020792/\sqrt{f}$$

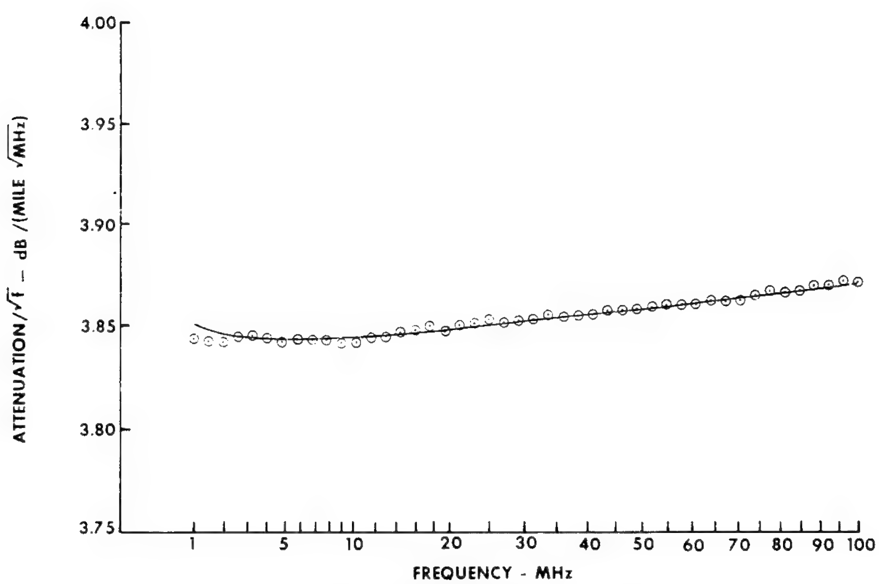

FIG. 2 - COMPARISON OF MEASURED AND FIT ATTENUATION FOR TYPICAL COAX. CIRCLED POINTS ARE MEASURED VALUES. SOLID LINE IS FIT CURVE. EQUATION FOR FIT CURVE IS

$$\alpha/\sqrt{f} = 3.8227 \left(1 + \frac{.0062}{\sqrt{f}}\right) + .00455\sqrt{f}$$

PAPER INSULATED TELEPHONE CABLES

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SUMMARY

Paper is the oldest form of telephone cable insulation in current use and has been noticeably absent in the literature in spite of marked technical progress in recent years. This paper reports the state of the art and emphasizes, particularly, recent developments. Longitudinal insulation, both of single wires and pairs, is described and is compared with plastic, pulp, and spiral ribbon insulation. The use of aluminum conductors with paper and pulp insulation is discussed, with test results and field experience presented - particularly on corrosion aspects.

INTRODUCTION

Paper and pulp have been the principal means of insulating telephone cable conductors for more than 80 years, but during the last three decades there has been increasing use of the modern plastic materials as alternatives. Over this period, major R & D effort and almost all published technical literature has concentrated on this latter form of the product.

The early death of cellulose insulated cables in favor of plastic has been repeatedly predicted for over 15 years. In spite of these prophets, however, the use of paper (including pulp) as a telephone cable insulant continues to grow. ITT associate companies in Europe, (including the two cited in this paper, Standard Telephones and Cables Ltd. (STC) and Standard Electrica, S.A. (SESA)), South America, Africa, and Australia manufacture both plastic and cellulose insulated telephone cables. Each have their place but since the plastic story has been so completely told, the present paper will attempt to put the current position of paper insulated telephone cable into its proper perspective.

Figure 1 illustrates the growth of paper insulation in recent years in some of the major telephone-using countries of the world; indications are that the growth will continue, although possibly at a reduced rate.

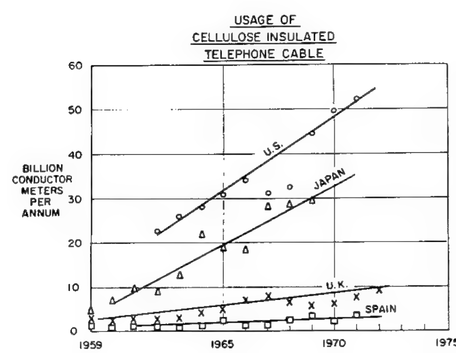


Fig. 1 Growth in use of cellulose insulated telephone cable over the last decade for representative free world countries.

HISTORY

The first commercial telephone exchange was opened in the U.S.A. in 1878. The following year the first appeared in Europe, and a year later the first true telephone cable was

laid across the Brooklyn Bridge.[1,2] Cables used for these early telephone systems followed existing telegraph cable practice, using either rubber or gutta percha as an insulant. These proved unsatisfactory for telephony and were soon superseded by various types of impregnated textile insulant.

The first major advance in telephone cable technique was the introduction in 1890 of air spaced paper ribbon insulation. The first cable of this new type to be used in Europe was laid by the Western Electric Company (the forerunner of the present Standard Telephones and Cables Limited) in 1891 between Liverpool and Birkenhead (through the Mersey Tunnel).[3]

In the U.S. these early cables were 0.9 mm (#19 AWG) copper conductor, the cable having a mutual capacitance of 50 nf/km (0.08 mfd/mile), therby setting a standard very little changed today.

In some of the earliest European dry core cables, the insulating paper was applied longitudinally.[4,5] The problem of maintaining the shape of the insulation around the wire and preventing unwrapping proved a constant source of trouble, however. The solution most frequently adopted was to bind the insulation with a helical lapping of cotton which cut deeply into the paper tube, thus imparting a twisted appearance to the resulting product - hence the name "balloon type insulation" which was given to it in England and Germany.

In these early days conductor diameters were large (2.5 mm and 2.8 mm being quite common) and both the machinery available and the quality of materials was such that high speeds were not possible. The first significant step forward was that of applying the paper in a very extended helix (a technique which has recently been revived in much-improved form in Japan) so that the tension in the paper would tend to hold it in position around the wire. This led to the discovery that better capacitance balances could thereby be achieved in the multiple twin (DM Quad) form of construction, and this gave rise to the use of a much closer spiral application of the paper and to the long series of now well-known spiral lapping machines.

The first serious competition to air space paper ribbon came in the early 1930's when the Western Electric Company (U.S.) introduced the direct application of pulp to the wires, so forming the paper layer (again longitudinally applied) in situ.[6] The early pulp insulated cables had mutual capacitance levels approximately 25 per cent higher than those of similar ribbon insulated cables. This impairment in transmission efficiency was considered prohibitive for inter-office cables and objectionable for all types, but the indicated savings in cable first cost were sufficient to warrant further development and today cables of the two types are approximately equal in size for the same mutual capacitance.

The next serious competition came in the early 1950's when the bulk production of low molecular weight polyethylene for the consumer goods industry so reduced the price that the material became economically attractive as a telephone cable insulant. The introduction of polyethylene insulation and sheathing (in lieu of lead) resulted in a sudden cost advantage for cables with a low pair count; it also introduced several new problems which will be discussed later.

Customer acceptance of these alternative methods of conductor insulation resulted in increasing pressure being put upon the machine designer to apply spirally applied paper at even greater speeds. However, no substantial improvement resulted, since at the same time, conductor diameters were decreasing requiring the use of narrower and thinner strips of delicate paper.

In the early 1950's, therefore, an attempt was made to re-examine the possibility of using longitudinally applied paper as an insulant, and a number of designs were made by Standard Telephones and Cables Limited (STC), an ITT associate, all of which were based on the principle of passing a heavily moistened strip of paper through a forming die which was maintained at a high temperature.[7,8]

Insulation made by these early processes tended to unravel, however, and proved difficult to joint, so that the original development program was abandoned in 1954. It was, however, resuscitated on both sides of the Atlantic[34] in the mid-1960's and has since proved highly successful, the secret of its success being the use of an adhesive to seal the paper overlap - thus inspiring the STC name for the product "Sealed Paper Tube (SPT) Insulation".[9, 10, 11, 12]

This basic development has subsequently been refined to cover the simultaneous longitudinal insulation of the two wires of a pair with a single strip of paper having twin sealed overlap and a weakened connecting web for ease of jointing. This further improved form of insulation - known as "B Type SPT" - was introduced by STC in 1972.[13, 14]

MANUFACTURING METHODS

Helical Paper Ribbon Insulation

The earliest machines for applying helical paper ribbon insulation had the pads of paper mounted external to the wire. The whole pad revolved eccentrically around the wire axis and the insulation speed was therefore very slow. In later designs, the pads were mounted concentric with the wire. Since the load on the head was then balanced, much greater speeds were possible. By the mid-1910's paper head speeds had increased to 3000 r.p.m. and general machine improvements had permitted the construction of cables having up to 1212 pairs of 0.51 mm (#24 AWG) conductor within a sheath that 20 years previously had contained a maximum of only 152 pairs 0.90 mm (#19 AWG). Over the past 50 years, little significant further change has been made. Figure 2 shows a group of modern helical paper ribbon insulating machines at STC's North Woolwich plant.

Pulp Insulation

Pulp insulating utilizes paper making principles. Pulp is shipped dry and must be made into a slurry by mixing with water and neutral soaps.

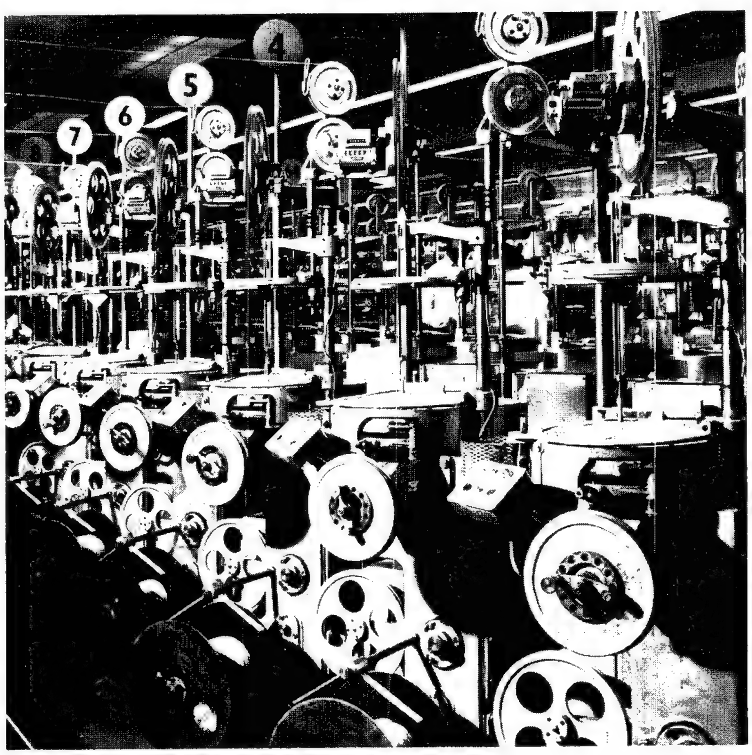


Fig. 2 A group of helical-wrap insulating machines at the STC cable plant in North Woolwich, England.

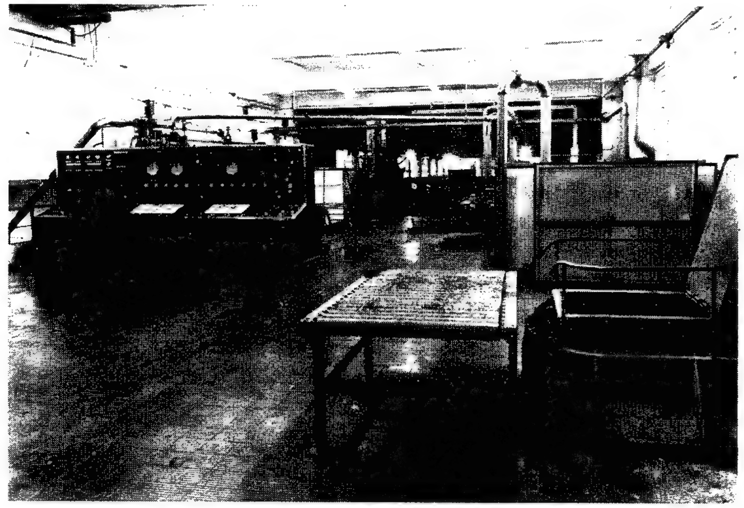


Fig. 3 A portion of the pulp preparation area at SESA cable plant in Santander, Spain.

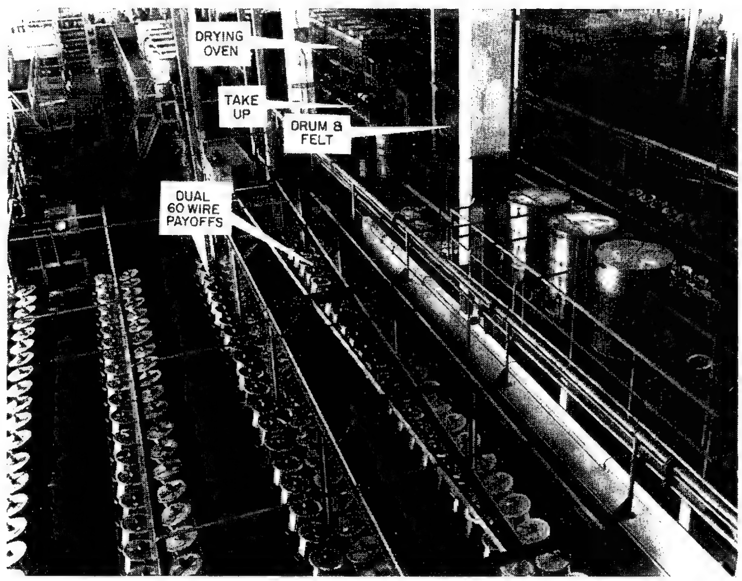


Fig. 4 Portion of pulp insulating area at SESA. Key machine elements are labeled.

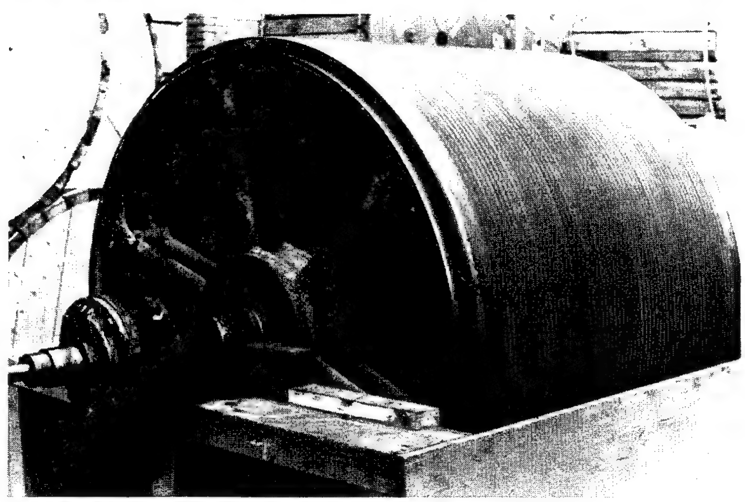


Fig. 5 Close up view of drum (before installation into the machine) which applies ribbon of pulp to bare wire.

Figure 3 shows part of the pulp preparation area of Standard Electrica, S.A. in Santander, Spain (an ITT associate).

The slurry is then picked up by a drum over which 60 wires pass for about 190° over the circumference. A flat ribbon of wet pulp is picked up by each wire, partially dried on a felt belt, and wiped into a uniform circular layer by a rotating die. The pulp is then dried into a paper layer in an oven before the wire is taken up on reels for pair twisting.

Figure 4 shows a pulp insulating area with the key portions indicated.

Figure 5 shows a drum as used to apply the strips of wet pulp to the bare wires prior to installation of the drum in the machine.

Longitudinal Paper Insulation

- SPT (Sealed Paper Tube)

In this new form of insulation, a tape of special paper is longitudinally wrapped around each conductor in such a way as to provide a minimum of two thicknesses at any point. During the forming process, a fine jet of moisture-resistant adhesive is applied to the overlap, which sets immediately to form an efficient and durable seal, thus preventing unravelling during subsequent processing and jointing.

A sketch of the resulting insulation form is shown in Figure 6A, and a typical cable having this form of insulation is shown in Figure 7. Figure 8 shows a group of four SPT machines in production.

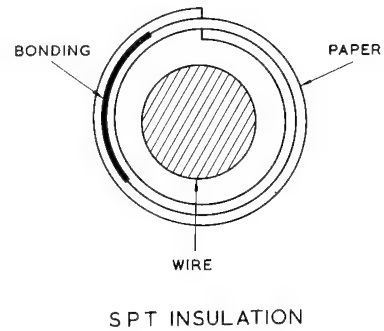


Fig. 6A Sketch of SPT insulation.

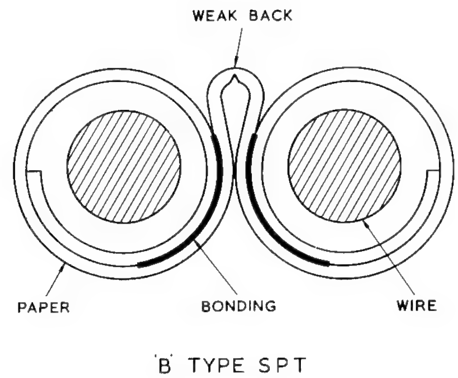


Fig. 6B Sketch of "B" type SPT.

Fig. 7 SPT insulated telephone cable.
1600 pair 0.5 mm (#24 AWG) with four cellular polyethylene video pairs in the center.

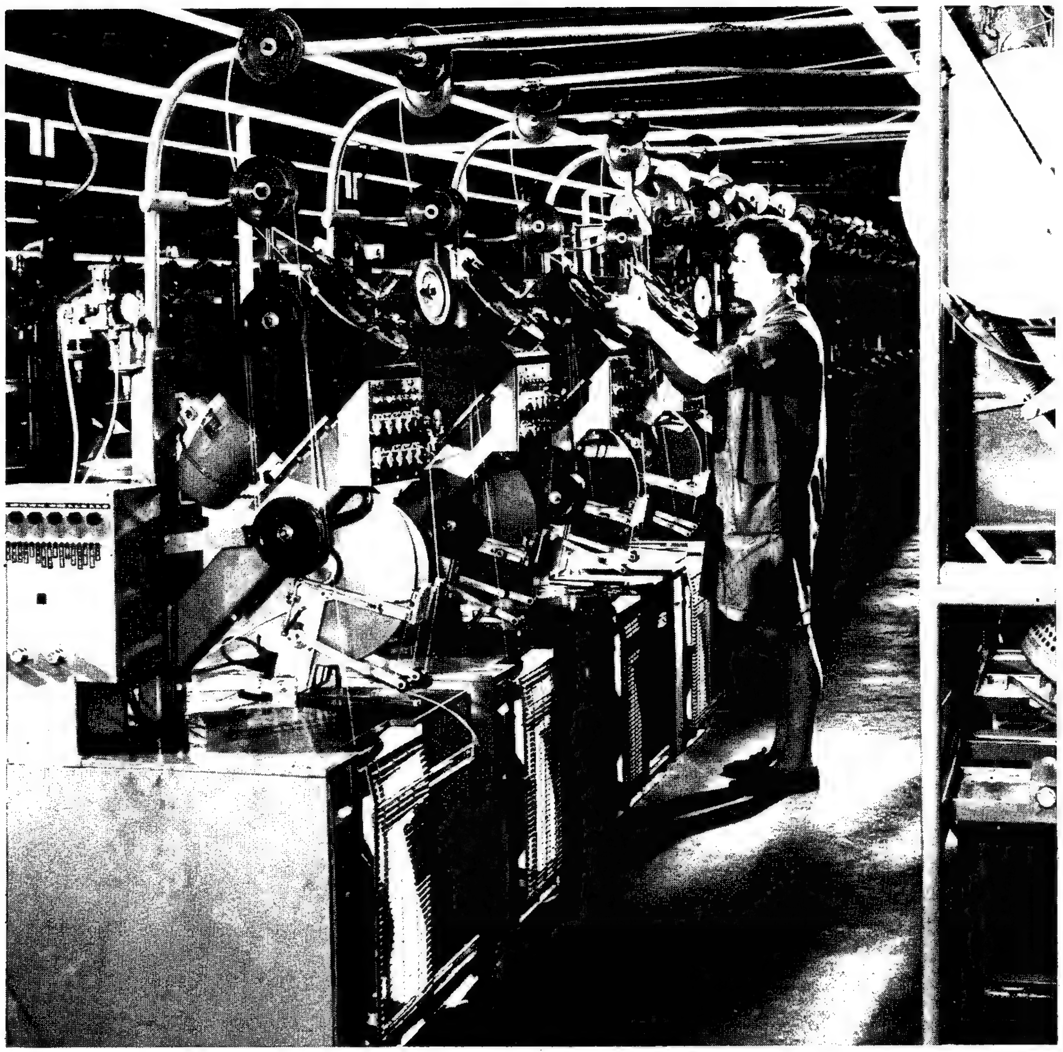


Fig. 8 A group of production SPT machines at the STC cable plant in North Woolwich, England.

- B Type SPT

The manufacturing process is similar to that used for the basic SPT form of insulation except that now two conductors are insulated simultaneously with one paper tape. After this insulation has been formed and sealed, it is passed through a device where the connecting web between the two insulated conductors is weakened to permit easy separation. A sketch of the resulting insulation form is shown in Figure 6B, and a photograph of a cross-section of an actual cable is shown in Figure 9. This photograph illustrates clearly the vast amount of air insulation present in a paper cable. A typical cable having this form of insulation is shown in Figure 10. Figure 11 shows a close-up of the die used for the combined insulation process.

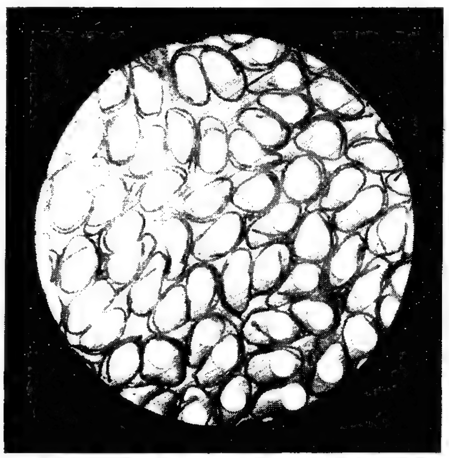


Fig. 9 Cross-section of "B" type SPT cable, magnified 10 times. Note the large amount of air insulation typical of paper ribbon cable.

SPT INSULATION

One might ask why the decision was made to enter into a costly development program for a new form of paper ribbon insulation at a time when the pulp insulation process had become well established and polyethylene was appearing to be rapidly replacing paper as a preferred telephone cable conductor insulant. The answer is that in spite of its antiquity, air spaced paper insulation can still offer a number of significant advantages to both cable maker and cable user. In conventional helical form, it also possesses a number of serious disadvantages. The primary object of the SPT development program, therefore, was to eliminate as many as possible of the undesirable features while retaining all those which were advantageous.

Some of the most important differences between helical paper, longitudinal paper, pulp and plastic insulations are discussed in the sections which follow.

Dielectric Constant, Mutual Capacitance and Cable Size

The ideal insulation material for a telephone cable is air, which has a dielectric constant of unity and a power factor of zero (this ideal situation is, of course, very nearly achieved in the special case of disc-spaced coaxial cable, the insulation of which is 95% air). Except in the special case of fully filled cables, the dielectric of a cable pair consists of a non-homogeneous mixture of solid insulating material and air. The greater the

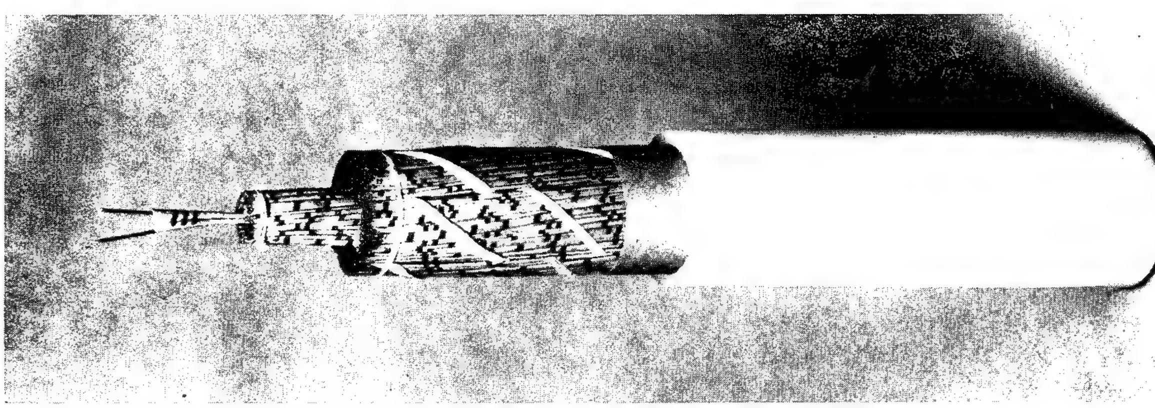


Fig. 10 "B" type SPT insulated telephone cable. 300 pair 0.5 mm (#24 AWG).

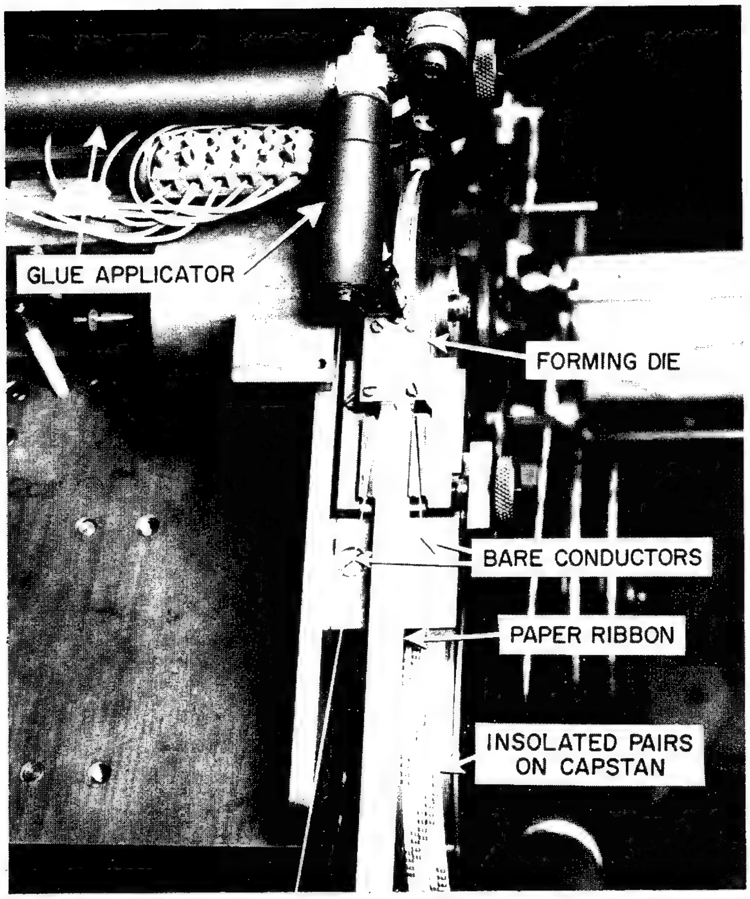


Fig. 11 Close-up of forming tool for "B" type SPT insulated with key machine elements labeled.

amount of this solid matèrial, the higher its inherent dielectric constant and the nearer its proximity to the conductor (where the electric field is strongest), the greater is the effective dielectric constant (εeff) of the composite dielectric and hence the greater is the mutual capacitance - which is directly proportional to the dielectric constant. Alternatively, if the effective dielectric constant increases and the mutual capacitance is kept constant, the larger is the cable diameter for a constant number of pairs or the smaller is the number of pairs which can be contained within a constant sheath diameter. Of course, with fully filled cables, the dielectric constant is higher because the air is replaced by filling compound.

Typical values of effective dielectric constant recorded at the various ITT cable factories in Europe are given in Table 1.

TABLE 1

Effective Dielectric Constant Values for Typical Cable Constructions

Type of Insulation	εeff
Helical Paper Longitudinal Paper Cellulose Pulp Cellular Polyethylene, Non Filled	1.55
Solid Polyethylene, Non Filled Cellular Polyethylene, Fully Filled	1.85
Solid Polyethylene, Fully Filled	2.25

Cable size differences resulting from these values of εeff are shown in Figure 12.

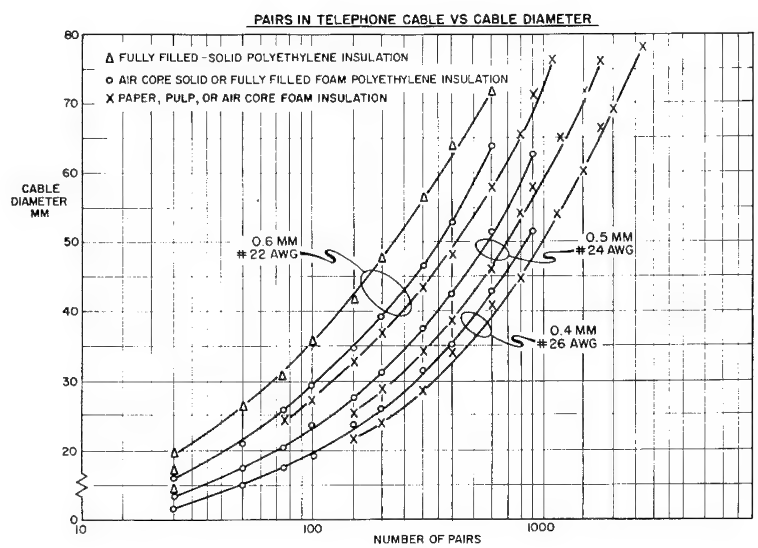


Fig. 12 Cable Diameter v. Pair Count for various cable constructions.

Moisture Attack

Hydrophobia is usually defined as "an unnatural fear of water". The cable man's fear of water, however, is far from unnatural, since more circuit failures occur as a result of water entry into the cable than from any other single cause. There are two distinct mechanisms by which water can enter a cable, and their results on the system performance are quite different. These are discussed in some detail in the sections which follow.

Water Entering via Sheath Diffusion

The mechanism of moisture vapor diffusion through a plastic sheath is well-known and has been adequately documented in past Symposium papers.[15] The important features which must be remembered when considering the effects of water entering a cable via sheath diffusion are as follows:-

a.) Diffused water is free from inorganic electrolytes and has a high degree of purity.

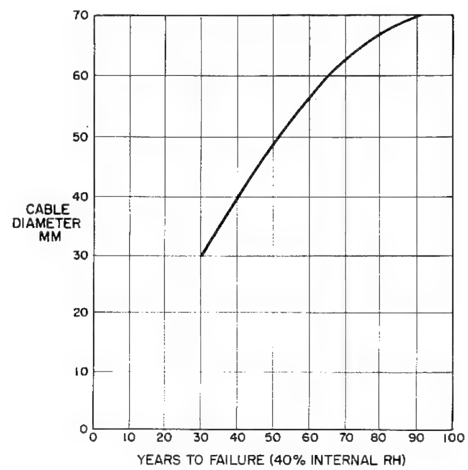
b.) Moisture vapor diffusion is a relatively slow process which is vitally affected by the sheath construction (in particular by the quality of any moisture barrier present).

c.) Diffusion occurs throughout the length of a cable exposed to high levels of external relative humidity (R.H.) or immersed in water.

Bearing these factors in mind, and referring to the substantial amount of available technical literature on the subject, the behavior of the various types of insulation in the presence of diffused moisture vapor can be seen to be as follows:-

a.) Helical Paper Ribbon Insulation

When moisture vapor enters an air-spaced paper insulated cable it is taken up by the composite dielectric in a uniform manner, resulting in a gradual deterioration in the insulation resistance. Detailed studies carried out by the BPO[16] have shown that practical cables, insulated with paper sensibly free from impurities and sheathed with an extrusion of polyethylene reach their effective terminal resistance when the internal RH has increased to about 40%, equivalent to a paper moisture content of just under 7%. The condition would be reached after a period of time dependent upon the amount of paper within the sheath. Typical calculated values of time to failure for different sizes of BPO cable exposed to external conditions of 100% RH at a temperature of 15°C, are plotted in Figure 13.



Should any impurities exist in the cable dielectric (through the use of poor quality paper or from the incorrect selection of printing inks, cottons, etc.) the times to failure could be significantly reduced but under all normal conditions an adequate service life can be assured through the inclusion in the sheath structure of a metallic barrier, even of the simplest form.

Considerable evidence has been produced to show that the sealed polyethylene aluminum laminate sheath which has replaced lead in many countries will improve the effective cable life by up to two orders of magnitude.

b.) Pulp Insulation

With pulp, a number of materials need to be added to the basic cellulose to assist production. Provided these are chosen with care, the behavior of

pulp insulated cables in the presence of diffused moisture vapor can be made to be very similar to that of paper cables. Curves of moisture content v. relative humidity v. insulation resistance produced by Bell Telephone Laboratories for pulp insulated cables [17], do in fact, show a good degree of correlation with those produced by the BPO for helical paper cable in the study mentioned above.

c.) Longitudinal Paper Insulation

With either form of SPT insulation, the only material not found in conventional paper ribbon insulation is the overlap sealing adhesive.

The adhesive finally selected is insoluble in water and completely non-ionic. Tests carried out by STC have substantiated that the behavior of this insulation in the presence of diffused moisture vapor is identical with that of helical paper.

d.) Non-Filled Polyethylene Insulation

Moisture vapor permeating through the sheath of a non-filled solid polyethylene insulated cable can result in a rapid rise in RH within the cable core (unless, as is current BPO practice, wrappings of paper tape have been included primarily as a desiccant to retard this rise). In little more than a year, the RH can rise to such a value that a sudden drop in ambient temperature will bring about condensation onto the insulation surfaces. In addition to seriously affecting the high frequency electrical characteristics of the pairs, [18] such condensed water can cause localized corrosion at pinholes under operating cable conditions. Both effects are made considerably worse if any contaminants exist on the polyethylene surface (e.g. impurities picked up in the cooling trough of the extruder or deposited on the surface by electrostatic attraction during subsequent processing). For this type of cable, therefore, an efficient barrier must be included in the sheath structure.

e.) Non-Filled Cellular Polyethylene Insulation

The moisture vapor diffusion and deposition process is the same as for non-filled solid polyethylene cable, but the effects are usually more serious since the pinhole incidence is normally greater. Also, if a chemical blowing agent is used, there is the additional danger of permeated moisture activating its residue.

f.) Fully-Filled Polyethylene Cable

In a fully filled cable, the only places moisture vapor can migrate to are voids in the filling material or gas cells in the insulation if cellular polyethylene is used. Hence, in theory, no metallic barrier in the sheath structure is necessary. In practice, however, such a barrier is often included to reduce the risk of external interference and to prevent the filling material from migrating through the sheath, thus making the outside of the cable slippery and more difficult to joint.

Water Entering via Sheath Damage

The problems which arise when water enters a cable via sheath damage are only too well-known to all cable users - they also form the main topic of Session III of this present Symposium, [19, 20, 21] hence, discussion of the subject in this present paper will be kept as brief as possible.

The important features which must be remembered when considering the effects of liquid water entering a cable via a sheath fault are as follows:-

a.) The water entering is almost always far from pure.

b.) The process is speedy.

c.) The area of entry is highly localized.

The behaviors of the various types of insulation in the presence of such water can be

summarized as follows:-

a.) Pulp and Paper Insulated Cables (All Types)

- Almost immediate failure of all circuits (note, however, that in the special case of cables having aluminum conductors continuity may be temporarily re-established - see later section of paper).

- Swelling of the insulation, thereby forming a block which effectively stops any further entry of water.

Thus the damage is sudden and serious but confined to a few meters of cable - and is capable of being located with a high degree of accuracy. The faulty portion, therefore, can (and must) be quickly found, opened up and repaired. This feature is particularly advantageous in the case of buried cable.

b.) Non-Filled Polyethylene Cables

- Often no immediate circuit failure (unless the sheath damage is, for example, caused by a spade cut).

- Water gradually travels along the cable, causing shield corrosion, a general degradation in transmission properties and, ultimately, conductor failure at insulation pinholes or at badly-insulated joints.

Thus the damage is usually slow to manifest itself, serious when it does occur and is spread over a considerable length of cable. Moreover, it is difficult to locate and even more difficult to remove once it has been located.

Many Administrations feel it is impossible to establish a workable maintenance program with non-filled plastic cable. If water gets in it may be months or years before trouble shows but, when it does pair after pair over a period of time will be lost often with no way of getting at the basic fault.

c.) Fully Filled Polyethylene Cables

- Although water may enter the cable, none travels along it. Hence, usually, transmission is unaffected.

In summary:

1.) Any of the cellulose cables offer the important advantage of quick positive fault location with ability to repair.

2.) Fully filled plastic cable solves the water entry problem at a price of much higher monetary cost, larger size or higher capacitance, and unpleasantness in handling.

Factory Processing

A typical medium-volume telephone cable manufacturing plant, of the type common throughout Europe, would have an output of the order of 5 - 6 B.C.M. of insulated conductor per year divided about equally between plastic and paper (or pulp).

In most cases, the product mix is dictated by the customer - however, the supplier can have a great influence via technical information and pricing policies.

In the sections which follow, rough comparisons are given of the various insulating processes from the manufacturer's point of view for production quantities of about half the total plant amounts indicated above.

a.) Capital Cost and Floor Space

The relative costs of the types of machinery under consideration, together with their relative floor space requirements, are shown in Table No. 2, using the helical paper process as a basis.

TABLE 2

Relative Costs and Floor Space Requirements for * Various Types of Insulating Machine

Type of Machine	Initial Cost	Floor Space
Helical Paper	100%	100%
Longitudinal Paper	60%	25%
Plastic Extrusion	140%	225%
Pulp	280%	250%

* Based on conditions prevailing in the various ITT cable factories

b.) Machine Flexibility

The typical medium-volume cable plant is called upon to produce a multitude of sizes, types and insulation markings, hence a reasonable degree of flexibility in the manufacturing process is essential. This can be achieved by the use of a large number of machines or by the use of a process which can be readily changed. Both are true for helical paper and the latter for SPT. Lack of flexibility is the main reason that pulp insulating machines are rarely found outside the Americas and Japan, where the size of the market, the size of the factories and the high degree of standardization of the product makes pulp a viable proposition.

c.) Manning Requirements

The number of operators per machine varies considerably from plant-to-plant and from country-to-country. Throughout the various ITT cable factories, however, it has been found that for a given output the manning requirement of the insulating machines is approximately the same for pulp, plastic extrusion and longitudinal paper insulation and is equal to about one third of that for helical ribbon insulation.

d.) Processability

There is little difference in the ease with which the various forms of insulated conductor can be paired but, during the subsequent stranding operations, paper insulated conductors are generally easier to process than pulp or plastic since the insulation is soft and the pairs bed down together and can easily be died down to form a firm, round cable core.

Pulp and plastic insulated pairs tend to be "live" during the stranding operation and the resulting cables are generally less flexible than those having paper insulated conductors. In the special case of fully filled cables, of course, considerably more complex and expensive stranding facilities are required.

Jointing

There are four main conductor jointing methods in general use today.

These are as follows:-

a.) Hand Twisting Methods (Soldered or dry)

b.) Machine Twisting Methods (Japanese jointing gun, Canadian "Miller" machine)

c.) "Push In" Mechanical Methods ('B' connector, Scothlok)

d.) "Pull In" Mechanical Methods (BPO No. 4, AMP Picobond, 3M MS2)

Although still very widely used throughout the world, the hand twisting methods which have existed since the beginning of the art are gradually being replaced by the modern mechanical methods.[35] The two machine twisting methods have been included for the sake of completeness only. In the past, they have found little popularity outside their countries of origin and they, too, are now being replaced by methods (c) and (d).

Detailed investigations carried out in the STC jointing development laboratories have shown the comparative jointing behaviors of the various types of conductor insulation to be as follows:-

a.) Helical Paper Ribbon Insulation

Hand Twisting Methods: Generally satisfactory

Machine Twisting Methods: Poor, due to insulation unravelling

"Push In" Mechanical: Bad, due to insulation rucking back

"Pull In" Mechanical: Generally good, except for the MS 2 method, where shiners form

b.) Pulp Insulation; Non-Filled Cellular Polyethylene Insulation

Easy to joint by all four methods - although, with pulp, occasional shiners have been encountered when using the Miller machine.

Both types of insulated conductor are a little more "alive" than those insulated with paper, hence handling problems are slightly increased. An additional complication with pulp is that the poor coloring system inherent in this process makes pair identification difficult under practical installation conditions.

c.) Longitudinal Paper Insulation

Easy to joint by all standard methods. In the B type SPT form, separating the two wires of a pair is a necessary prelude to jointing - except in the special case of the dual-head AMP picobond machine (type MA8), which is ideally suited to this form of insulation - but this slight disadvantage is more than offset by the assured freedom from split pairs. Figure 14 shows a joint being made in SPT insulated cable using "B" wire connectors.

some areas.

A significant conclusion from the laboratory comparison was that each type of cable possessed a specific handling characteristic which affected the jointing time. For want of a better term, this characteristic was defined by the investigating team as the "Jointing Facility (J.F.) Factor". The J.F. factor is determined by such features as the surface nature of the insulation and its physical strength, the overall diameter of the insulated

Fig. 14 Jointing SPT insulated cables with "B wire" connectors.

d.) Non-Filled Solid Polyethylene Insulation

Solid Polyethylene is the most difficult of all forms of insulation to strip for hand-jointing, but it is easy to joint on all machines. Conductors having this form of insulation are decidedly "springy", hence care is necessary in order to avoid split pairs.

e.) Fully Filled Polyethylene Cables

Generally as for (b) and (d) above. The presence of the filling compound tends to kill the springiness of the insulated conductors. It also makes the task of jointing unpleasant to perform - particularly in the case of the exceptionally sticky filling compounds now being used in

wire, the temper of the conductor material and also by the lay length of the pair twist.

As the science of machine jointing grows and time-cutting becomes of crucial importance, the J. F. factor of the cable is every bit as important as the speedy operation of the machine. It is false economy to increase jointing speeds by using the latest machines while at the same time slowing down the process by using cable conductors which are difficult to select and handle.

Jointing machine tests at STC have shown that the jointing speeds of paper insulated conductors are faster than those of polyethylene insulated conductors and that

length of the pair has an optimum value with present conventional twisted pair. It has also been shown that the longer twist lengths which are possible with the "B" type SPT form of construction improve the J. F. factor. A similar change in most other forms of construction will reduce the J. F. factor because of pair confusion, which results in the jointing of crossed pairs.

Clearly, there is a great future for paper insulated conductors in the machine jointing age, and in particular, longitudinal paper insulation.

ALUMINUM CONDUCTORS

The abundant and relatively inexpensive supply of aluminum in the world requires its consideration as a telephone cable conductor material, especially in view of the volatile fluctuation of copper prices and the control of its supply by relatively few and often politically unstable countries.

Aluminum is attractive for this purpose and aluminum conductor cables are in production in several countries and under consideration in several others.

In the United States, EC grade aluminum cables in 0.8 mm and 1.1 mm conductor sizes (#20 and #17 AWG) are in large scale production [22, 23] and trials are underway on 0.5 mm (#24 AWG).

In the U.K. and France, large quantities of cable having 0.5 mm (#24 AWG) aluminum conductors are in production. [24, 25] These cables use cellular polyethylene insulation and are fully filled with petroleum jelly. Current production is up to 100 pairs, but field trials are under way including cables of up to 1600 pairs. In the U.K., earlier cables, which have now been in service for up to 5 years, had conductors of 0.8 mm and 0.6 mm (#20 and #22 AWG).

Although paper insulated aluminum conductor cables are not currently in such large-scale production, it is on this type of cable that the greatest amount of long-term field experience of aluminum exists. On the continent of Europe, there are many cables still in service which were installed during World War II and which used aluminum conductors with paper insulation.

In the U.K., over the period 1953 to 1960, the BPO conducted a substantial field trial of aluminum conductor telephone cables. A total of just over 40 sheath km of cable was installed, embracing 4200 conductor kms and involving more than 30,000 conductor joints. [26, 27] Most of the cable was paper insulated and polyethylene sheathed, but about 10%, on a conductor km basis, had polyethylene for both conductor insulation and sheath.

A length of cable from the first of these trial schemes (a 51 pair 0.5 mm paper insulated cable installed in the Guildford area in 1953) has recently had to be withdrawn from service because of sheath damage. The BPO have conducted a thorough examination of this cable and has reported no detectable deterioration in the properties of the conductors, which were 3/4 hard EC grade aluminum. Until the time of the sheath damage, service performance was reported as having been satisfactory. In fact, the maintenance performance of all the field trial cables has been stated by the BPO to have been substantially the same as that which would have been expected from copper conductor cables operating under similar conditions.

Perhaps, the most famous aluminum conductor cable to be installed by the BPO during this exploratory period - certainly the one most frequently quoted in the technical literature - was the 14.5 km route between Dover and Deal in Kent. [28] This was a 54 pair paper insulated cable, having 1.1 mm (#17 AWG) aluminum conductors and a non-barriered polyethylene sheath. It was installed in a standard BPO duct in 1954/55, and is still giving satisfactory service.

Similar trial installations of paper insulated aluminum conductor cable have taken place in Australia, [29] with lead sheathed cables in the earlier stages (1965-1970) having been followed more recently (1969-1971) by cables sheathed with barriered polyethylene.

In contrast to these success stories with aluminum conductors a number of disasters point to the need for careful cable design, installation, and operation.

The greatest potential problem with aluminum conductors is the possibility of

corrosion should moisture penetrate the cable. We will, therefore, examine the effects of moisture as described above for each form of construction, first for permeated moisture and then for water entering through a sheath fault.

Water Entering via Sheath Diffusion

a.) Paper

Both helical paper and SPT insulation (with proper adhesive) behave identically and will be treated together. As discussed above, paper insulation which is sensibly free from impurities reaches its terminal insulation resistance when the internal cable RH reaches 40%. Therefore, we need to study the possibility of corrosion only at internal RH values lower than 40% since the cable is unusable above this level.

Work done independently at STC [30] and in Australia [31] shows that no corrosion of aluminum conductors can be expected over the normal life of paper insulated cable at internal RH levels up to 40%. As pointed out above, the adhesive chosen for SPT is non-ionic in nature and not soluble in water and does not affect the conductor in any way under the above conditions.

b.) Pulp

Similar studies of aluminum conductor under pulp insulation carried out at SESA [32] indicate that when the pulp additives are chosen with care, there is no danger of corrosion over the cable life when the RH is under 40%. However, additional tests have shown that small additions of either sulphate or chloride ions will rapidly increase susceptibility to corrosion. Just as impurities in the pulp or paper can accelerate corrosion so can inclusions on the wire surface. As part of the test program at SESA, some aluminum wire was deliberately passed through a drawing machine normally used for copper without changing the solution, insulated with high quality pulp, and subjected to accelerated corrosion tests. This wire, therefore, had copper particles embedded in its surface picked up from the dirty solution. Corrosion pits developed in the immediate vicinity of the copper much sooner than on pure aluminum as shown on Figures 15 A-C. Figure 15 A shows pure aluminum and Figures 15 B and 15 C show areas of corrosion which started from embedded copper particles.

Of course, had the ionic impurity content of the pulp been high, electrolytic corrosion at the copper impurities would have been even more pronounced. It should also be pointed out that the manufacturing process for pulp would tend to increase the possibility of corrosion if conditions were not correct, since the conductor is insulated wet and then subjected to a very high temperature for the initial drying out process.

c.) Non-Filled Plastic

As pointed out earlier, if no paper is added to the construction, the internal RH will rapidly rise and a sudden temperature drop will produce condensate on the insulation surface. In addition to the deleterious electrical effects, such condensed water can cause rapid localized corrosion at pinholes, particularly if there is surface contamination on the insulation.

d.) Filled Plastic

With filled plastic insulation, water does not penetrate and, therefore, the problem does not exist.

Water Entering via Sheath Damage

In the case of sheath damage, the end result is no different than for copper cable except that, with non-filled plastic insulation, corrosion of conductors is normally much more rapid. The mechanism of failure in paper and pulp cables however, is quite different.

As mentioned above, water entering after sheath damage is usually far from pure and hence, usually forms an electrolyte, thereby considerably accelerating the corrosion process.

a.) Paper and Pulp Insulation

With paper and pulp insulation the paper saturates, swells, and blocks further water travel. There is an initial loss of service, just as with copper conductors. However, after a period of an hour or two, service may be restored due to the build-up of an insulating layer of hydrated aluminum oxide on the conductors.

Service will then continue for a further short period of time until wire after wire

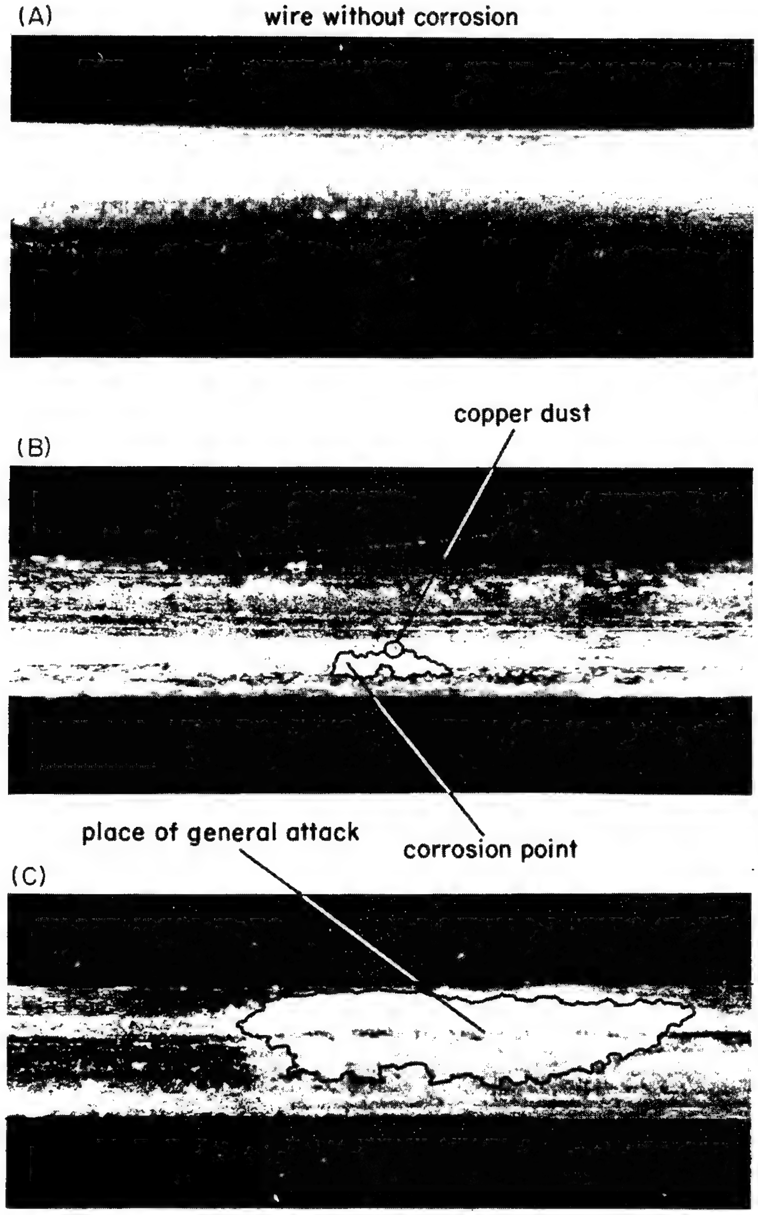
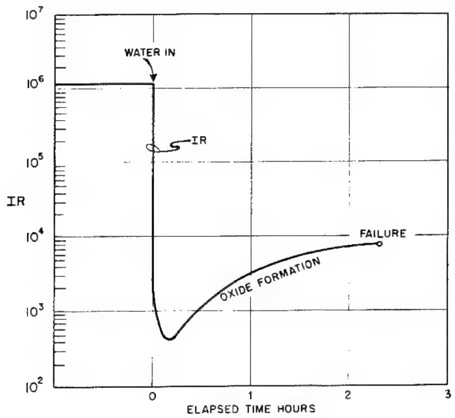


Fig. 15 Effect of copper dust embedded in aluminum conductor surface. Pulp insulated wires were subjected to 60% relative humidity for periods up to 90 days and then stripped of the insulation and examined visually.

fails completely through complete oxidation (Figure 16).



This mechanism often hinders the location of the damaged area, although it could well be overcome by the inclusion in the cable of one or more wires made of copper or similar non-corrosive metal to be used as a monitor and fault locater.

Under these circumstances, the delay period between the entry of water and final circuit failure could well provide the time necessary to locate the fault and unearth the cable while service was still maintained.

This failure mode has been observed in the field and confirmed in ITT laboratories in England and Spain.

b.) Non-Filled Plastic

Water enters and travels just as in copper cable until it meets pinholes in the insulation or badly-made joints. Localized conductor corrosion at these points is particularly severe due to the high current density. Complete separation of the conductor can occur in 1 to 2 hours.

c.) Filled Plastic

Identical with copper cable.

In summary, aluminum conductor is suitable for use in telephone cables with any insulation system provided the design and application is proper.

Paper or pulp insulated cables with aluminum conductors have been in service for many years. The insulation used on these cables should have a minimum of impurities and no copper particles should be on the conductor.

With pulp, special care is needed because of processing conditions. Sheaths should utilize a moisture barrier and the cable should preferably be pressurized. Further, a completely reliable sheath closure method should be employed.

SPT DEVELOPMENT

When the decision was made at STC in 1965 to re-examine the possibility of applying insulating papers longitudinally, attention was first turned to the unsuccessful previous attempts in the early 1950's, and the conclusion was drawn that most of the problems that had been encountered at that time had originated from the use of a heated forming die. It seemed obvious, therefore, that any future process should be based upon the longitudinally applied tape being formed by a cold die and then being held in place by some form of adhesive.

It was also realized, from the considerations discussed in the previous section of this paper, that the final process must above all else have two characteristics:

(a.) It must produce robust and contact-free insulation which would be easy to handle both in the factory and in the field.

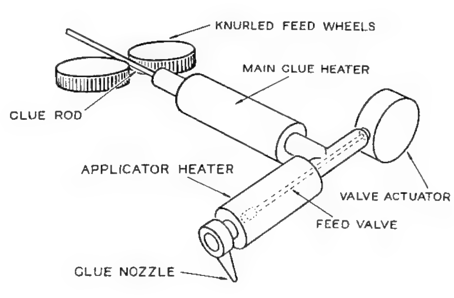
(b.) It must achieve a high output per man-hour of insulating operative.

With these overriding considerations in mind, a system was devised in which the insulating paper was formed around the wire by means of a die, and a narrow strip of adhesive was placed along one edge of the paper immediately before this edge was formed into the complete tube. The tube was then held in place for a short time by wrapping it around a

capstan wheel, thus providing time for the adhesive to set. This process proved mechanically successful, and a number of experimental lengths of cable were produced in which the adhesive used was an emulsion of latex rubber in water. Unfortunately, the emulsifying agent used in this adhesive was ionic in character and the insulation resistance of the resulting cable failed to comply with the exacting requirements of the British Post Office. (6500 Megohm km). Considerable work was then done to establish which type of adhesive would be most suitable to both the conditions of the process and the requirements of the product, and it was finally decided that the high-temperature melting resins commonly called "Hot Melt Adhesives" were the best family of adhesives to use. Means were then devised to make it possible to use these types of adhesive and further development was based on the use of a polyamide resin as the adhesive material.

The application of a controlled quantity of hot resin glue to the insulating paper in a process of this nature presents several difficulties. A very small amount is required, it must be applied evenly and in a precise position, and it must be possible to start and stop the process without affecting the glueing efficiency.

The device finally adopted (Figure 17), met the requirements without complication. It consists of a heated tube having an application nozzle jet and on/off valve at one end and a cooled section at the other end. Glue is supplied in the form of an extruded rod, its diameter being a reasonable fit in the cooled section of the applicator tube. It is driven into the tube by friction wheels which are mechanically coupled to the machine capstan. This accurately controls the rate of delivery irrespective of machine speed.



The glue rod is melted in the applicator tube and the feed pressure forces molten glue between the rod and the tube, but the combined effect of the cooled section and the cold glue rod cause this glue to re-freeze on the rod and provide an effective seal. The on/off valve prevents slow leakage when stationary.

A coupled control moves the applicator jet to and from the operating position when the machine starts and stops.

Another major decision taken during the early stages of the development of this insulation was to wrap the insulating paper twice around the wire (see Figure 6A). Although, fairly difficult to achieve from the forming point of view, it had two distinct advantages. One was that, in the event of partial failure of the glue seam, there was little prospect of the copper wire escaping, and the other was that the strip of paper required to achieve this was much wider than would otherwise be the case - and the added width increased the stability of the paper pads, thus enabling much larger pads to be used and reducing the labor required for paper changes.

When running at the high speeds which are achievable with longitudinal paper insulation, the advent of a paper break would normally cause a considerable amount of bare wire to be wound on to the take-up bobbin while the machine came to rest; this would then need to be wound back before a repair could be made. It was, therefore, essential to cause a rapid arrest of the insulating machine in the event of a fault condition arising in the product. This has been achieved by making the mass of the moving parts as low as possible and by instituting a special controlled deceleration time which is applicable to fault conditions being detected. Deceleration from full running speed has been achieved in a distance of less than 2 meters. This makes it possible to pull back and make a repair and continue operation with very little wasted time.

In a further attempt to reduce down time to a minimum, the insulating machines have been designed to accommodate pads of paper containing nearly 3,000 meters length. As this has to be supplied to the insulating die with a running tension between 200-250 grams, a considerable

tension control problem needed to be overcome. The paper pad has an inside to outside diameter ratio of 1:5 and consequently, its rotational speed varies by the same ratio. The need for low pull-off tension, and rapid arrest in the event of a fault, precluded the use of either rotating or stationary support plates which are normally used to guide paper pads. The mechanism which has been developed to meet these requirements is completely novel. It allows the paper pad to rotate without side support and maintains the paper supply tension within close limits by a brake which operates on the extreme edge of the pad.

The machines which finally evolved from this development are shown in Figure 8. The first field trial of cables made on these machines took place in 1971, when the British Post Office installed a total of 5.7 km of cable, ranging in size from 200 to 2000 pair, mostly having 0.4 mm diameter (#26 AWG) copper conductors, in a new subscribers' network radiating from the Sidcup (Kent) Exchange. The installation proved entirely satisfactory, and BPO type approval for this form of cable insulation was given in February 1972. Later in the year, the first major export contract for cables insulated by the SPT process was completed. This was for 13.4 km of cable containing 1600 SPT pairs having 0.5 mm (#24 AWG) copper conductors together with 4 cellular polyethylene insulated video pairs for direct transmission of television. A photograph of this somewhat unusual cable is shown in Figure 7.

The effectiveness of the sealed tube form of insulating on this cable was well demonstrated by the fact that although the usual 16 spare pairs were included, approximately 50% of all drum lengths were, in fact, completely fault-free and 95% of all drum lengths contained 3 faulty pairs or less. Further the average breakdown voltage (wire to all other wires connected to the moisture barrier) was 2.3 Kv, as against 1.3 Kv normally recorded on cables of this type insulated with conventional helical paper.

As development of the basic SPT process progressed, it became apparent that a logical step forward would be to insulate the two wires of a pair simultaneously with a single paper ribbon, thereby achieving the following additional advantages:-

- A significant increase in output per machine.
- Greater operating stability, due partly to the use of double-width supply pads and partly to the balanced nature of the resulting forming die.
- Complete avoidance of "split pairs" thereby considerably facilitating the jointing process and permitting the use of substantially longer twist lengths (this in itself providing a further aid to jointing).
- Improved resistance unbalance and earth capacitance unbalance characteristics, due to the assured length equality of the two conductors of a pair.

Initial experiments verified that the paper forming and sealing operation was as simple with two wires as with one, and a prototype machine embodying this principle was completed in 1972. Apart from the addition of a second wire supply stand, the only other significant alteration found necessary to be made to the basic SPT machine was the inclusion of a device to weaken the web of paper connecting the two insulated conductors, thereby enabling the two wires to be separated easily at the jointing stage (see Figure 6B). A number of experimental cables have been successfully made on this prototype machine, one of which is shown in Figure 10; routine manufacture on the final production version of this machine is planned to commence in 1973.

FUTURE DEVELOPMENT

Since the development of pulp cable in the early thirties, R & D on cellulose insulated cables stagnated until plastic entered the picture as a competitor.

This competition re-initiated development effort, the two most significant results of which were the replacement of lead by the much less expensive barrier sheath and the introduction of the SPT form of conductor insulation as described above.

In the future, effort will be required to further reduce cost through raw material substitutions - through, for example the introduction of aluminum conductors and lower cost papers. The paper industry is alive with new

paper/plastic laminates and papers made from synthetic fibers.

Improved twisting, stranding and cabling methods will be needed to reduce crosstalk levels due to p.c.m., upgraded subscriber loops and switching systems where cables will be used. There is every indication that the "B" type SPT form of insulation will prove particularly suitable for this purpose. In addition, improved high frequency characteristics will be available for p.c.m. applications.

Smaller gauge sizes to 0.32 or 0.25 mm (#28 or #30 AWG) will be used in areas of short loops and high concentration where duct space is valuable.

CONCLUSIONS

1.) Paper insulated telephone cable growth has been steady and is expected to continue.

2.) Improvements are to be expected in cable construction, paper materials, and electrical properties as a result of increased R & D.

3.) The SPT type of insulation described in this paper has advantages over helical paper as follows:-

   a.) It does not ruck up on "push-in" jointing devices.

   b.) It is easier to handle and joint.

   c.) Shiners are eliminated.

   d.) There are fewer contacts in manufacture.

   e.) Dielectric strength is improved.

   f.) Less manufacturing space is needed.

   g.) The capital cost of machinery is lower.

   h.) The output per operator is greater.

In "B" type form, it also has the advantages of lower resistance unbalances and improved capacitance unbalance to earth, easier handling and positive identification.

At the same time, both forms of SPT insulation retain the following very important advantages of paper:-

   a.) Water is blocked from longitudinal flow due to paper swelling.

   b.) Faults due to water ingress are localized and easy to find.

   c.) The dielectric has a low material cost.

   d.) The resulting cable is small in size.

4.) If desired, aluminum conductor can be used with paper insulation if design and application is proper.

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A CORRUGATED, WIRE-FILLED ALUMINUM SHEATH TO SCREEN TELEPHONE CABLE FROM INDUCTIVE INTERFERENCE

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Summary

A corrugated, steel-wire-filled aluminum sheath has been developed as a screening sheath to protect telephone cable from inductive interference from power systems. This sheath provides satisfactory lower stiffness and higher screening effect even in a cable of the largest size. Besides the structural details and reduction to formulas of the additional inductance and resistance due to the magnetic flux and iron losses in the steel armoring, results of tests on screening and mechanical properties and other factors are presented and discussed.

Introduction

In telephone cable technology, interference between power system and telecommunication line is a problem of long standing. To reduce the interference due to magnetic induction from power system, many studies on the compensation effect of a telephone cable sheath, as well as on effective sheath structures, have been made since the early 1920's. However, new development of an efficient screening sheath providing higher compensation effect is a theme still worthy of being challenged in Japan today, where high speed railways are electrified with 20~25kV a.c. and high and super-high tension transmission lines with direct grounding system are rapidly expanding their networks throughout the country.

Based upon experiences gained with steel tape armored lead sheath cables used for screening, an active study for more efficient cable screening against the magnetic induction started in Japan, with the beginning of electrification of the National Railway traction system. Various cable sheathings, including permalloy tape armored lead sheath and a specially composed sheath involving a longitudinal copper shield were tested. The varied experimental studies in laboratories and in the field finally resulted in the introduction of aluminum sheath cables with steel tape armor. In fact, among others, the aluminum sheath gives practically the lowest longitudinal resistance, which, together with the high magnetic permeability of armoring steel tape, is essential for effective reduction of induced voltage. All coaxial and signalling cables being installed along the New Tokaido Line for the purpose of communication and the centralized traffic control were protected with steel armored aluminum sheath.

In 1960, aluminum sheath cables armored with low carbon steel tapes were introduced into the public telephone network as well, for application where the magnetic induction from power transmission lines and a.c. railways was a problem. Since then, some 2000 km of this type of cable, supplied by Dainichi-Nippon Cables, have been installed in network of Nippon Telegraph and Telephone Public Corporation (NTT).

In addition to efficient screening ability, adequate mechanical properties of aluminum sheath has greatly contributed toward reliable cable performance. However, with the increase of the demand, both in volume and in cable size, a peculiar property of aluminum, stiffness of the cable, caused a problem. Though this stiffness had not been too serious as far as smaller cables were concerned, it was causing considerable reduction of flexibility in larger cables. Consequently, when the cable diameter was over approximately 40 mm, easy handling of the cable could no longer be expected.

The high Young's modulus of elasticity also was a concern. When a cable, installed aerially or in underground conduit, is subjected to annual temperature cycles, a considerable internal stress can be built up in the sheath. Hence, proper measures must be taken to absorb or suppress the eventual thermal expansion or contraction in order to protect the cable splices and sheath joints. In practice, the slack-method is adopted, in which cable installation contains a certain amount of slack at every pole or in each manhole. A reinforced cable splice and sheath joint is another approach to the problem. But these methods require sub-

stantial manpower and extra cost, particularly in cables of larger sizes.

To obviate these problems, further investigation for a cable of statisfiable properties has long been desired.

Fundamental Screening Factor Formula

At first, we shall review some fundamentals of screening theory.

In general, the compensation effect of a cable sheath with a ground return is evaluated by the screening factor defined as the absolute value of the ratio of resultant induced e.m.f. in the screened cable conductors to the primary e.m.f. which would appear in the absence of the screening sheath. The resultant induced e.m.f. per unit length, when the sheath is perfectly grounded, is equal to the product of current density on the inner surface of the sheath and d.c. resistivity of the sheath, therefore, the ratio of the surface transfer impedance to the series impedance of the sheath gives the intrinsic screening factor of the cable.

In the case of aluminum sheath, however, the cable must have an insulating protective jacket against corrosion, so that the grounding resistance is no longer negligible. Thus, as the working screening factor s, we obtain

$$s = \frac{R_1 + R_3}{\sqrt{(R_2 + R_3 + R_4)^2 + \omega^2 (L_4 + L_5)^2}} \tag{1}$$

where R_1 is the surface transfer impedance of the armored sheath, which is identifiable with the d.c. resistance R_0 in the commercial frequency.

R_2 is the effective resistance of the sheath and approximately identical with R_0 in the commercial frequency.

R_3 is the grounding resistance, including the resistance of the ground return.

R_4 is the additional resistance due to the iron losses in the steel armor.

L_4 is the additional inductance due to the magnetic flux in the steel armor.

L_5 is the external inductance of the sheath and ground return circuit.

Because of the nonlinear magnetic properties of steel armor, the screening factor is dependent on the sheath current I, therefore, it depends on the following primary induced e.m.f. V,

$$V = I \cdot \sqrt{(R_2 + R_3 + R_4)^2 + \omega^2 (L_4 + L_5)^2} \tag{2}$$

Assume that the screening sheath consists of a cylindrical pipe of homogeneous material. If D is the average diameter of the pipe, δ the wall thickness, σ its resistivity and μ the permeability, the inductance is given by $\mu\delta/(\pi D)$ while $R_0 \doteqdot \sigma/(\pi D \delta)$. Introducing the complex permeability $\mu = \mu_r - j\mu_i$ with regard to iron losses, we have

$$\omega L_4 = \frac{\omega\,\delta}{\pi\,D}\,\mu_r \tag{3}$$

$$R_4 = \frac{\omega\,\delta}{\pi\,D}\,\mu_i \tag{4}$$

where μ_r and μ_i are material constants dependent only upon the field intensity and frequency. When we let $r_0 = R_0 \cdot D$, $r_4 = R_4 \cdot D$ and $\ell_4 = L_4 D$, all of them become independent of the diameter. Substituting these factors into (1) and (2) and neglecting L_5 because $L_4 \gg L_5$, s and V can be written in the forms

$$s = \frac{r_0 + R_3 \cdot D}{\sqrt{(r_0 + R_3 \cdot D + r_4)^2 + (\omega \cdot \ell_4)^2}} \tag{5}$$

$$V = \frac{I}{D}\sqrt{(r_0 + R_3 \cdot D + r_4)^2 + (\omega \cdot \ell_4)^2} \tag{6}$$

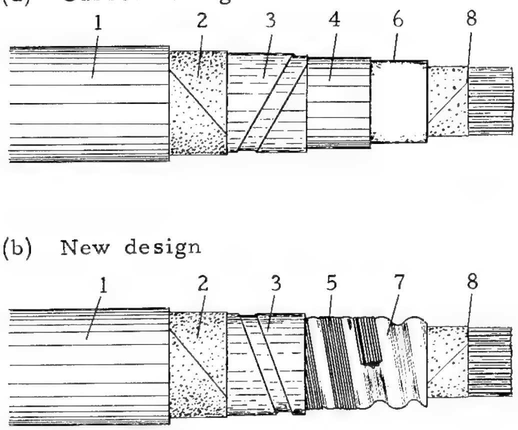
In practice, the grounding resistance is small as compared with the total series impedance, so that, under the same induced voltage, the sheath current is nearly proportional to the diameter. Subsequently, the magnetic field in the sheath is maintained at almost the same intensity, regardless of its diameter. Therefore, it can be deduced from (5) that the screening factor of a cable whose grounding resistance is R and sheath diameter is kD (k is a multiplying coefficient), is practically equivalent to that of another cable whose diameter is D and grounding resistance is kR, provided that both screening sheaths are composed of the same material of the same thickness. This reciprocal relationship between sheath diameter and grounding resistance on screening effect, is very important to the present problem.

New Design of Wire-Filled Corrugated Aluminum Sheath

Figure 1 (a) is an illustration of the

(a) Current design

(b) New design



1 Polyethylene jacket
2 Compounded cotton tape
3 Steel tapes
4 Inner polyethylene jacket
5 A bundle of steel wires wrapped into the corrugation
6 Smooth aluminum sheath
7 Corrugated aluminum sheath
8 Cable core

Fig. 1 Structure of Cables, Aluminum Sheathed and Steel Armored

standard sheath structure of the current cable. It is obvious that the high degree of stiffness of the cable is chiefly due to the smooth form of the aluminum sheath. There are many useful designs of higher flexibility. Among them, corrugation of the aluminum sheath is likely to be a most effective and practical means to decrease the stiffness of cable. The longitudinal Young's modulus of elasticity of a corrugated aluminum sheath has been shown to be equivalent to that of lead sheath.

The corrugation, on the other hand, brings about an unfavourable increase in sheath diameter, which would cause an eventual reduction of screening effect, as stated previously. As an example, take the case of 0.9mm x 100 pair cables sheathed with 1.5mm thick aluminum. The outside diameter of the corrugated sheath is 42.5mm, which is 20% greater than that of the smooth sheath. The armoring for both cables consists of two open spiral layers of 0.8mm low carbon steel strips. Table 1 shows their screening factors, measured under standard test condition with a grounding resistance of 2 ohms/km according to NTT's specifications.

Considerable decrease in screening effect is seen in the corrugated sheath. As compared with smaller cables, even the screening factors of the smooth sheath in Table 1 are substantially degraded, so that there is no allowance for this additional reduction.

As a countermeasure against this reduction, a corrugated aluminum sheath of sufficient wall thickness was examined. But this proved to be unsatisfactory because the cable gained a high degree of stiffness comparable with that of the smooth sheath cable, as is shown in Fig. 6.

It is likely that the improvement of screening factor gained by additional application of armoring steel is more effective for cables to be used with high grounding resistance. However, steel tape armoring in multiple layers, or use of thicker tapes, will defeat the purpose. After several trials, a new sheath design was developed.

Figure 1(b) is an illustration of a new cable using this new sheath design, the most distinguishing feature of which is a bundle of steel wires wrapped in the depression of spirally corrugated aluminum sheath. Two low carbon, high permeablity steel tapes are lapped to bridge the gaps across the spiral.

Table 2 shows the dimensional outlines of the sheath for 0.65mm x 200 pair local cable and 0.9mm x 100 pair trunk cable. Due to the elimination of the inner polyethylene jacket as well as the reduction in thickness of aluminum sheath and steel tape, the overall diameter of the new cable is maintained at almost the same value as those of the current design with smooth sheath.

An extensive study was made on the material specification of the steel wire and several wires with different qualities were standardized. Although the new corrugated sheath is relatively thin and accordingly has high electrical resistance, no reduction of screening

Table 1 Screening Factor of 0.9mm x 100 pair Tape Armored Cables with Smooth and Corrugated Aluminum Sheath

Primary induced e.m.f. (V/km)	Screening factor at f=60Hz $R_3=2\Omega$/km $L_5=2$mH/km	
	Smooth sheath	Corrugated sheath
20	0.41	0.50
30	0.37	0.43
50	0.30	0.36
100	0.25	0.30
150	0.23	0.27
200	0.21	0.26
300	0.21	0.26

Table 2 Dimensional Outlines of Cables with Newly Developed Screening Sheath

Type and size of cable		Local Cable 0.65mm x 200 pair	Trunk Cable 0.9mm x 100 pair
Type of insulation		Paper ribbon	Foamed polyethylene
Cable core	diameter	26.1 mm	32.2 mm
Aluminum sheath	thickness	1.0 mm	1.0 mm
	diameter	35.1 mm	41.5 mm
	corrugation pitch	14 mm	14 mm
Bundle of steel wires	wire diameter	0.45 mm	0.45 mm
	no. of wires	64	81
Steel tape armoring	thickness	0.5 mm	0.5 mm
	width	25 mm	25 mm
	no. of tapes	2	2
Compounded cotton tape	thickness	0.25 mm	0.25 mm
Polyethylene jacket	thickness	2.0 mm	2.0 mm
	diameter	42 mm	49 mm

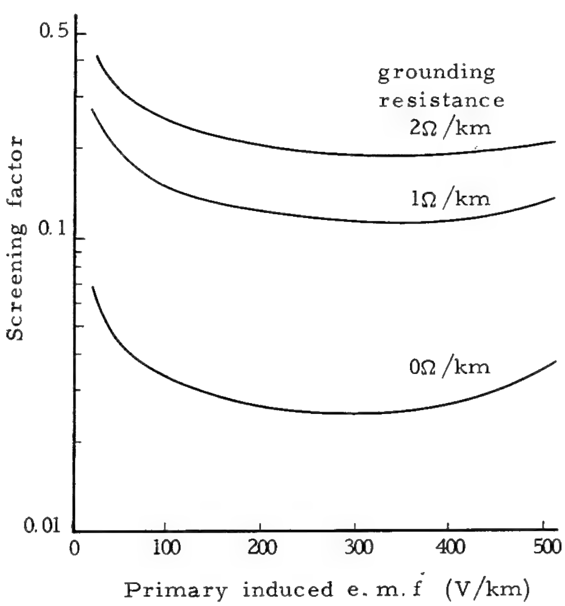


Fig. 2 Screening Factor of 0.9mm x 100 pair Cable with New Design Screening Sheath

Steel combination : Low carbon steel tapes and mild steel wire for general use

effect is observed, even in a cable filled with the inexpensive mild steel wire used for general purposes. When low carbon steel wires with high permeability are applied, the screening factor is greatly improved over the screening obtained by conventional tape armoring. Figure 2 is an example of the screening factor of 0.9mm x 100 pair cable in Table 2, armored with low carbon steel tapes and mild steel wires for general use. Measurements were made at 60 Hz and with an external inductance of 2 mH/km.

Steel Armoring Magnetic Properties

The effectiveness contribution of the armoring steels is evaluated to determine the screening effect of the cable. Reduction to formulas of the impedance components due to the magnetic flux and iron losses in the steels in this composite sheath is the present objective.

Magnetic Field Configuration

To begin with, an investigation is made of the magnetic field in the armoring. An a.c. current flowing through the aluminum sheath produces a magnetic field. The field in the

armoring is so complicated that its calculation by the analytical method would be impossible. However, a certain measuring technique is helpful to disclose the apparent field configuration.

Fugure 3 shows the arrangement of a cable specimen and test wires for the measurement. In the figure, the test wire 1L is one of the cable conductors. Wires 2L and 2S are placed between steel wires and inner steel tape, 3L and 3S between two layers of steel tape and 4L and 4S are outside the cable specimen. Test wires 2S, 3S and 4S are applied in spiral form while the remainings are laid straight.

From an induced voltage in a probing loop, which is formed with any two straight test wires, the circumferential or transverse component of magnetic flux passing through the area enclosed by the loop is obtained. On the other hand, a combination of an inner straight wire and an outer spiral wire gives the resultant voltage by transverse magnetic flux through the loop as well as by total longitudinal flux interlinked with the spiral. Varying the combination of test wires, all flux components in both transverse and longitudinal directions in each part of the sheath can be determined. Through measurement by an a.c. potentiometer, the absolute value as well as the phase angle to the current is determined for an induced voltage, from which the resistance and reactance components are separately obtained.

From these measurements, the following facts were disclosed.

(a) In the bundle of steel wires, the magnetic field is spiral. The apparent path of the magnetic flux almost (but not exactly) coincides with the spiralled steel wires.

(b) The magnetic field in either steel tape is also spiral. The magnetic flux in the inner layer passes along almost the same spiral, but with a rather greater helix angle, as that of the steel tape. However, the path of flux in outer layer considerably deviates from the spiral of the steel tape, which results chiefly from the reduction of longitudinal component of the flux.

(c) With respect to the transverse components of magnetic flux, which are effective for the screening factor of the cable, no interaction between steel layers was recognized through the experiments on the composite sheath as well as experiments on different test specimens with a single layer of spiralled steel. Therefore, it is deduced that the additional resistance and inductance due to all of the steel in this composite sheath are given by the total sum of those determined separately for each component layer of the armoring.

Formulas of Inductance and Resistance due to Steel Armoring

Valuable work has been done on the magnetic field in a single steel tape spiralled around a current-carrying conductor by U. Meyer and K. W. Wagner, upon the Krarup-conductor field structure.[1,2] According to Meyer, the magnetic flux in the covering of a Krarup-conductor, which consists of single open spiral of steel stripping around the conductor, passes, in spiral configuration with helix angle ψ, through the steel strip and across the gaps between turns, where helix angle ψ is given by the following relation.

$$\tan\psi = \frac{(b+g)^2 + b\,g\,N\sin^2\varphi}{b\,g\,N\sin\varphi\cos\varphi} \tag{7}$$

In the above formula, b is the strip width, g the gap width between turns, φ the helix angle of the spiralled strip, $N = (\sqrt{\mu_1/\mu_0} - \sqrt{\mu_0/\mu_1})^2$, μ_1 and μ_0 the permeabilities of the steel strip and air, respectively. When designating by δ the thickness of the strip, by D the mean

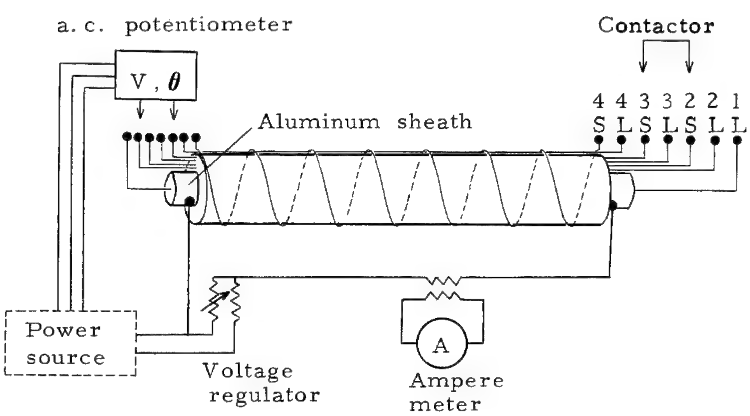


Fig. 3 Test Arrangement Used to Measure Impedance Due to Magnetic Flux in Steel Armoring

diameter of the covering, and by I the flowing current, the transverse component of the magnetic flux, per unit length, is obtained by

$$\Phi = \frac{I\,\mu_1\,\delta}{\pi D\,(b+g)} \cdot \frac{(b+g)^2 + b\,g\,N\,\sin^2\varphi}{b+g\;\;\mu_1/\mu_0} \qquad (8)$$

If p is the spiral pitch, $(b+g)$ can be replaced by $p\,\sin\varphi$, then, the following formula for the self-inductance of the conductor results.

$$L = \frac{\mu_1 \delta}{\pi D} \cdot \frac{b}{(b+g)} \cdot \sin^2\varphi\,\frac{p^2 + b\,g\,N}{b^2 + b\,g\,\mu_1/\mu_0} \qquad (9)$$

The first factor on the right hand is identical with (3) or (4), and the second and third factors represent the averaging and spiralling effect of the steel layer, respectively.

(a) Reactance and resistance due to steel tapes

In general, $N=\mu_1/\mu_0$, and p^2 and b^2 are negligibly small by comparison with bgN. Then, designating the number of steel tapes by n and introducing complex permeability $\mu = \mu_{tr} - j\mu_{ti}$, the following expressions are obtained for the additional reactance and resistance due to the steel tape armoring.

$$\omega L_{4t} = \frac{\omega\,n\,b\,\delta\,\sin^2\varphi}{\pi D\,(b+g)}\,\mu_{tr} \qquad (10)$$

$$R_{4t} = \frac{\omega\,n\,b\,\delta\,\sin^2\varphi}{\pi D\,(b+g)}\,\mu_{ti} \qquad (11)$$

(b) Reactance and resistance due to steel wires

When B is the total cross-sectional area of the bundle of steel wires, similar formulas for the steel wires are obtained by substituting $B/p\sin\varphi$ for $nb\delta/(b+g)$ in (10) and (11). Hence

$$\omega L_{4w} = \frac{\omega B\,\sin\varphi}{\pi D\,p}\,\mu_{wr} \qquad (12)$$

$$R_{4w} = \frac{\omega B\,\sin\varphi}{\pi D\,p}\,\mu_{wi} \qquad (13)$$

where μ_{wr} and μ_{wi} are the real and imaginary parts of the complex permeability of the steel wires.

Empirical Value of Permeability

In order to apply these formulas to the practical use, it is necessary to determine the numerical values of the permeabilities. As is well known, a mechanical strain imposed on steel material during armoring process gives rise to deterioration in magnetic permeability. Therefore, back calculations of the permeabilities from the measured impedance components on completed cables were made. Figure 4 shows the permeability curves of the low carbon steel tape and the mild steel wire for general use, which were obtained from the reactance and resistance due to the transverse magnetic flux in each armoring steel of 0.9mm x 100 pair cable.

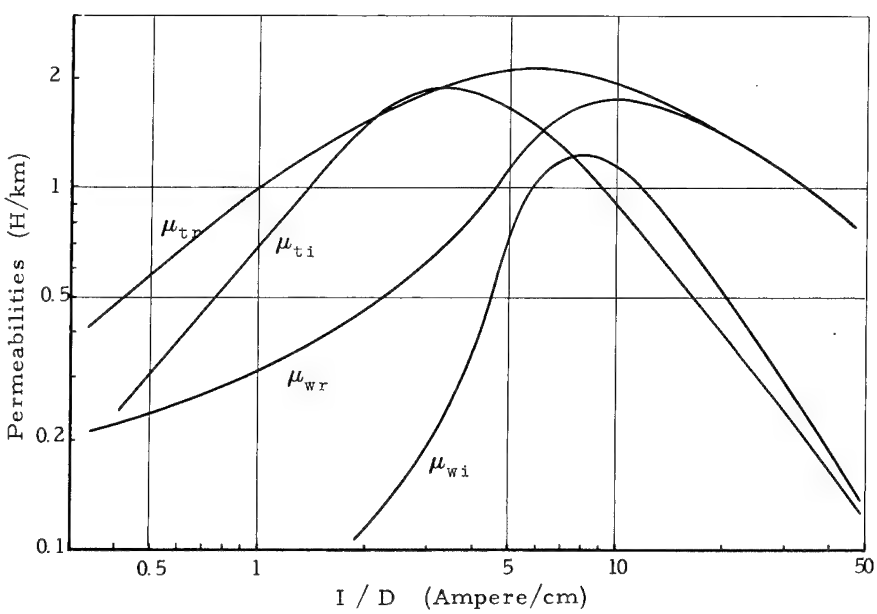


Fig. 4 Permeabilities of Low Carbon Steel Tape and Mild Steel Wire for General Use

I : Sheath current

D : Average diameter of steel wrapping

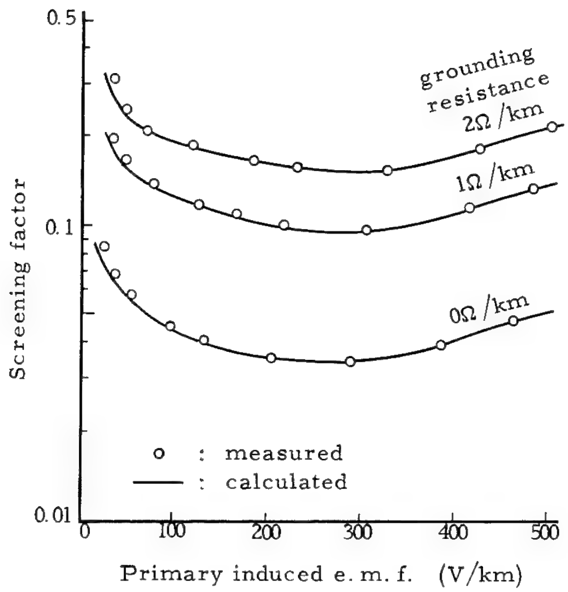


Fig. 5 Screening Factor of 0. 9mm x 28 pair Cable with New Design Screening Sheath

Steel combination : Low carbon steel tapes and mild steel wires for general use.

The validity of these permeability curves, as well as formulas (10)~(13), was proved through comparisons between calculated and measured impedance components on cables of different sizes.

Since the factors other than R_4 and L_4 in formula (1) are easily determined, an estimate of screening factor of this type of cable is now possible, using calculated values for additional reactance and resistance due to the armoring steel. The curves of Fig. 5 show the screening factors of 0. 9mm x 28 pair cable, thus calculated under conditions of a frequency 60 Hz and an external inductance 2mH/km. Measured values are also plotted in the figure, which show good coincidence with the calculated curves.

Mechanical Properties of The Cables

Flexibility

In order to evaluate the mechanical properties of the new cables, many tests were conducted. To determine flexibility, deflection test and bending test were made and, as will be stated below, both proved satisfactory improvement in cable flexibility.

Deflection Test Figure 6 shows an illustration of the test arrangement. The deflection of a cable laid on a pair of free supports was measured by a dial-gauge micrometer. Data are plotted also in Fig. 6 in relation to the increasing load weight. From these results, flexural rigidity EI is obtain by

$$EI = \frac{S^3}{48}\frac{W}{d}$$

where S is the distance between supports, W the load weight and d the deflection. The flexural rigidity of the cables for the elastic range, thus obtained, is given in Table 3. The EI value of the new cable is reduced to about 1/11

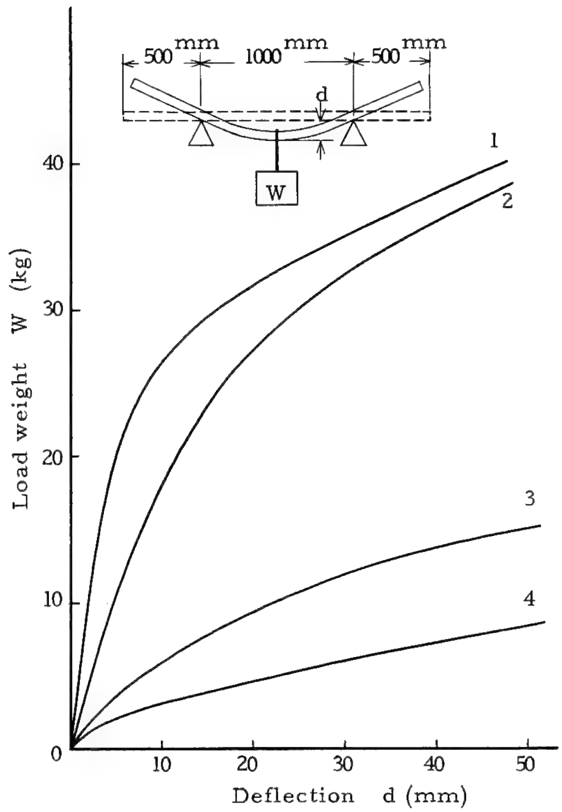


Fig. 6 Deflection Test

1 0. 65mm x 200 pair paper insulated cable with 1. 5mm smooth aluminum sheath armored with 0. 8mm steel tapes

2 Ditto, but with 2. 0mm corrugated aluminum sheath

3 Ditto, but with screening sheath of new design

4 0. 5mm x 600 pair paper insulated cable with stalpeth sheath

of that of the current cable.

Table 3 Flexural Rigidity of Cables

Cable No. in Fig. 6	E I ($kg\text{-}m^2$)
1	98.1
2	41.3
3	8.9
4	3.3

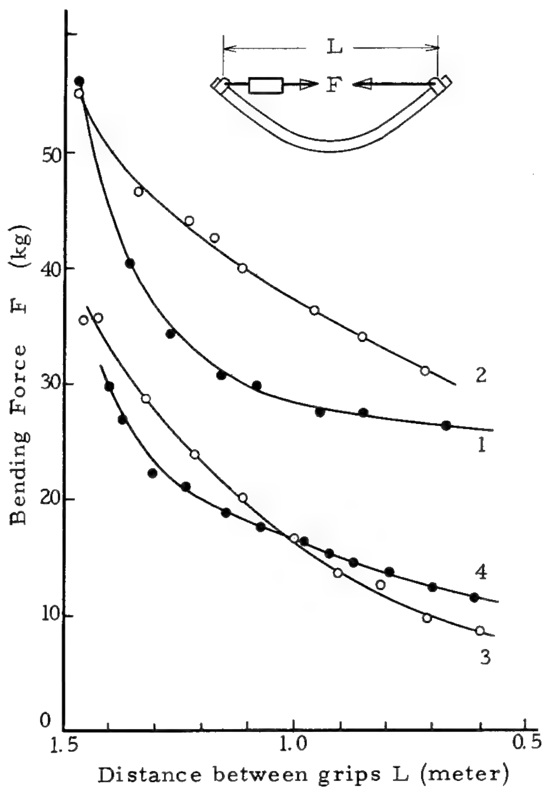


Fig. 7 Cable Pliability Comparison

1 0.65mm x 200 pair paper insulated cable with 1.5mm smooth aluminum sheath armored with 0.8mm steel tapes

2 Ditto, but with 2.0mm corrugated aluminum sheath

3 Ditto, but with screening sheath of new design

4 0.9mm x 100 pair paper insulated lead sheathed cable

Bending Test For simulation of actual field work, a bending test was conducted on the test assemblies shown in Fig. 7. In making the test, both ends of a cable specimen 1.5 meters in length are gripped by a rope, to which a tension meter is connected. When tightening the rope, the cable is forced to be bent into a curve.

The curves in Fig. 7 are the test results of the relation between increasing load and the linear distance between the grips. Evidently, the pliability of the new cable is improved to a point comparable with that of a lead sheath cable of equivalent overall diameter.

To examine the partial contribution of each layer of the sheath on the overall stiffness, similar bending tests on different test pieces of

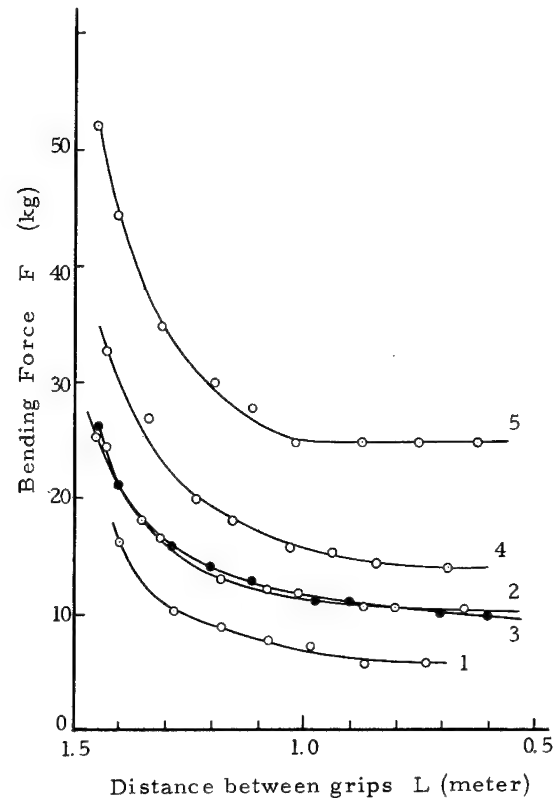


Fig. 8 Partial Effect of Cable Component on Overall Stiffness in 0.9mm x 100 pair Foamed Polyethylene Insulated Cable with Newly Designed Sheath

1 Corrugated aluminum sheath only
2 Cable core with aluminum sheath
3 After winding steel wires in the corrugation
4 After steel tape armoring
5 Completed cable

partially manufactured cable were made. Test results obtained from 0.9mm x 100 pair cable are given in Fig. 8. It shall be noticed that the winding of a bundle of steel wires adds very little to the overall stiffness of the cable. On the other hand, a marked difference between curves 4 and 5 is observed. However, this difference in bending force cannot be attributed to the stiffness of the polyethylene jacket alone, but to the combined effect of the steel tape and the jacket.

Stress-Strain Properties

The stress-strain property in the longitudinal direction of the cable is a very important factor in relation to the thermal stress in the sheath or the cable movement due to year round temperature changes. Therefore, in addition to the usual tensile test, stress-strain properties of cables in test conduit were examined.

Tensile Test

Figure 9 shows the stress-strain curves of the current sheath and the newly designed sheath for 0.65mm x 200 pair cable, measured by a conventional tensile test machine. The products of the modulus of elasticity and the effective cross-sectional area, determined from the curves, are also given in Fig. 9 by the designation AE.

Stress-strain Behaviour of Cable in Conduit

Because of the effect of "snaking" in installed cable, the actual stress-strain behaviour of cables in underground conduits will possibly be different from that of the test specimens in a tensile test machine. Therefore, the measurement was made on the cable test assembly with a load-cell and end blocks, which was built in a 75mm test conduit, as is illustrated in Fig. 10.

The compressive or tensile force on the cable was applied through the load-cell and end-block by forced movement of the end-cap fixed to the load-cell. The movements were measured by a dial-gauge micrometer in relation to applied force. The stress-strain behaviour of a cable being subjected to cycles of the compressive and tensile force, in general, shows a kind of hysteresis loop tracing the following course. (1) Snaking is gradually developed along the cable length under the increasing compressive force. (2) Partial spring back of the snake arises as compressive force is relaxed. (3) The cable is forced to be straight as tension is applied. (4) The cable is gradually stretched under the increasing tensile force. (5) Contraction of the cable occurs as tension is relaxed. (6) The cable is compressed back to its original length.

Figure 11 shows the stress-strain loops, thus obtained, of the current and newly designed sheaths for 0.65mm x 200 pair cable. The marked contrast between the two curves evidently indicates satisfactory reduction in the stiffness as well as Young's modulus of elasticity of the new cable. And it is seen that apparent modulus of elasticity in the compression side is generally less than that in the extension side.

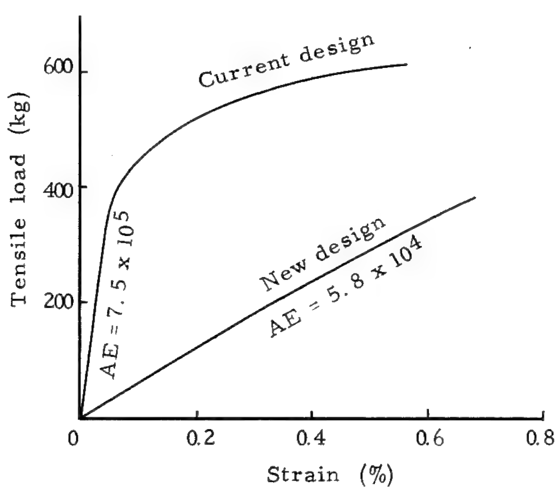
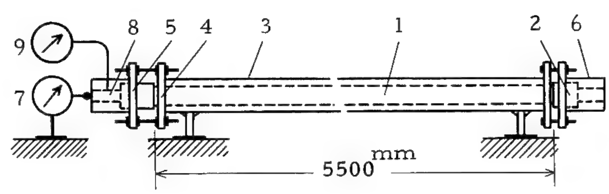


Fig. 9 Stress Strain Properties of Screening Sheaths for 0.65mm x 200 pair Cable



1 Cable specimen
2 End block
3 75mm test conduit
4 Conduit flange
5 Movable end-cap
6 Dead end-cap
7 Dial gauge micrometer
8 Load cell
9 Load cell indicator

Fig. 10 Test Arrangement Used to Determine Stress Strain Behaviour of Cable Lying in Conduit

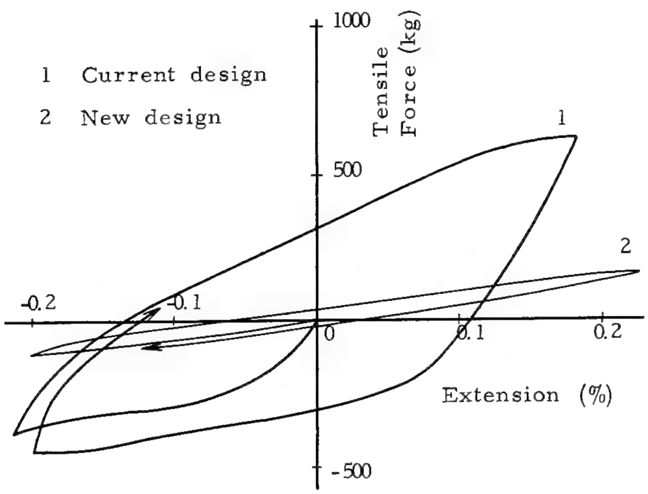


Fig. 11 Stress-Strain Hysteresis Loop of Screening Sheath for 0.65mm x 200 pair Cable under Cyclic Force

Cable Movement due to Temperature Cycles

An estimate is made of the thermal stress and eventual cable movement due to the temperature changes. When a cable of length L and weight per unit length w, lying in a conduit with coefficient of friction η and restraining force of F in manhole, is subjected to a temperature change t, the cable movement δL, given by the following formulas[3], arises.

when $\alpha t \geq (\eta w L + F)/AE$,

$$\delta L = \frac{L}{2}\left(\alpha t - \frac{F}{AE} - \frac{\eta w L}{4AE}\right) \tag{14}$$

when $\alpha t < (\eta w L + F)/AE$,

$$\delta L = \frac{AE}{2\eta w}\left(\alpha t - \frac{F}{AE}\right)^2 \tag{15}$$

where α, E and A are the coefficient of thermal expansion, the longitudinal Young's modulus of elasticity and effective cross-sectional area of the cable, respectively.

Take the case of 0.65mm x 200 pair cable for an example. For the current smooth sheath cable, employing the numerical values of $AE = 750 \times 10^3$ kg according to Fig. 9, $w = 3.4$ kg/m, $\alpha = 24 \times 10^{-6}$/deg. C and $\eta = 0.4$, and assuming that $t = 50$ deg. C and F = 0, we obtain $\delta L = 0.397$ meters from (15), where the section of cable from a free end to 661 meters is involved in the movement while the remainder is fixed by integrated frictional force. In order to suppress this movement, the restraining force F must be greater than 900 kg ($=\alpha t AE$).

On the other hand, the numerical values of AE and w of the new design sheath are 58×10^3kg and 3.5 kg/m, respectively. Then, for the free movement at $F = 0$, we have $\delta L = 0.0298$ m. In this case, only cable section 49.5 meters from a end, is involved in this movement. The minimum force required for suppressing the movement is 69.6 kg, which is small enough to be provided by the standard sheath joint.

Conclusion

The newly developed screening cable, having a corrugated aluminum sheath armored with a bundle of steel wires and additional steel tapes, has thus proved to be very satisfactory, both in screening effect and mechanical properties. Particularly, because of the remarkable reduction of the longitudinal Young's modulus of elasticity, the thermal stress built up in the sheath, due to the annual change of ambient temperature, can be reduced to a reasonable level, so that special countermeasures to protect the cable joints now become unnecessary.

Variations of this design will be applicable to cables which have a corrugated steel or other corrugated type metal sheath for screening purposes.

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A BONDED, NON-CORRUGATED ALUMINUM/POLYETHYLENE SHEATHING SYSTEM FOR TELEPHONE CABLE

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Abstract

With the current trend in telephone toward PCM and high frequency transmission, the electrical stability of cable becomes of significant importance. One of the prime factors in degradation of electrical characteristics is moisture. For this reason, Anaconda has developed a cable that for all practical purposes will prevent moisture permeation through the sheathing system. Along with this advantage, the construction also produces several significant improvements in the physical characteristics of the cable.

Introduction

With today's more sophisticated telephone systems, the previous concept that a polyethylene jacket would adequately keep moisture out of a cable is no longer completely true. For those who may not be convinced of this statement, there are three experiments that have been performed in our Laboratory that have considerable significance and offer some worthwhile background.

The first of these was a very elementary experiment using an 0.008 inch thick sheet of aluminum by 6 inches square with a 2 inch diameter bubble pushed out in the center to a height of ½ inch. A 0.015 inch thick polyethylene sheet, molded from jacketing material, was then bonded to the aluminum with adhesive, as shown in Figure 1. This sandwich construction was mounted as a cover over a vented vessel of water using an immersed heating element to provide steam at atmospheric pressure. After the polyethylene side of the specimen was subjected to the steam for 21 days, the sandwich was cut open and the bubble was found to contain water. A measurement by weight showed that approximately 1½ grams of water had entered the bubble during the 21 day period.

Now, what this experiment has demonstrated is the principle of osmotic permeation. If there is a differential of vapor pressures on two sides of a permeable sheet and a void is present, vapor will pass through the sheet by way of osmosis. Polyethylene provides such a permeable sheet as do almost all other materials. A differential in vapor pressures, as noted could be simply a difference in relative humidity on the two sides of the sheet or complete immersion in water.

The second experiment was devised to determine whether this principle of osmotic permeation would likewise apply to the more complex structure of a Telephone Cable Sheathing System. For this trial, a 50 foot length of 50 pair, 22 AWG Alpeth Exchange Area Cable was used. In case everyone is not familiar with this construction, the wrapped cable core is covered with an 8 mil corrugated aluminum shield and a 70 mil polyethylene jacket as shown in Figure 2. To prepare the sample, the conductors were elongated to reduce the core diameter so that the paired conductors plus the core wrap tape could be removed without disturbing the aluminum shield and polyethylene outer jacket. This hollow tube,

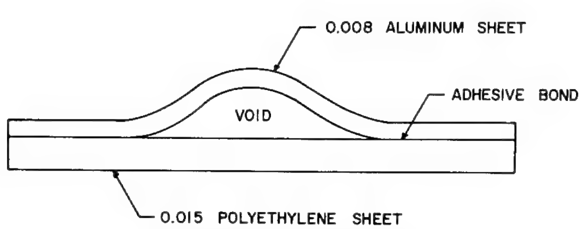

Figure 1 Cross-section of Test Sample

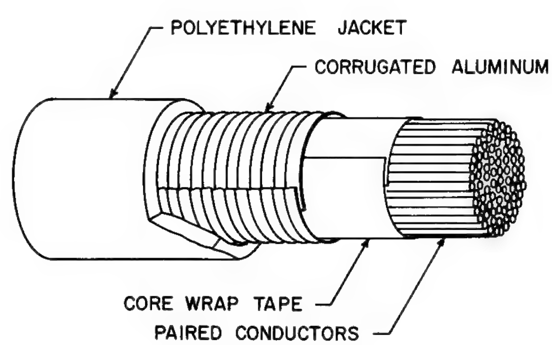

Figure 2 Alpeth Cable Construction

which constitutes the cable sheathing system, was used for the experiment. Tapered bronze plugs with centered copper tube connections were forced into each end of the hollow tube and sealed in place to make them gas tight. Copper tubing was then connected to both bronze plugs with one tube running to a tank of dry nitrogen and the other tube to a coulometric hygrometer calibrated in parts per million of moisture contained in the gas. The cable sheath assembly was placed in an environmental chamber held at 120°F and 100% relative humidity. Figure 3 shows a schematic drawing of this test-set with a by-pass line provided to measure the moisture content in the nitrogen source.

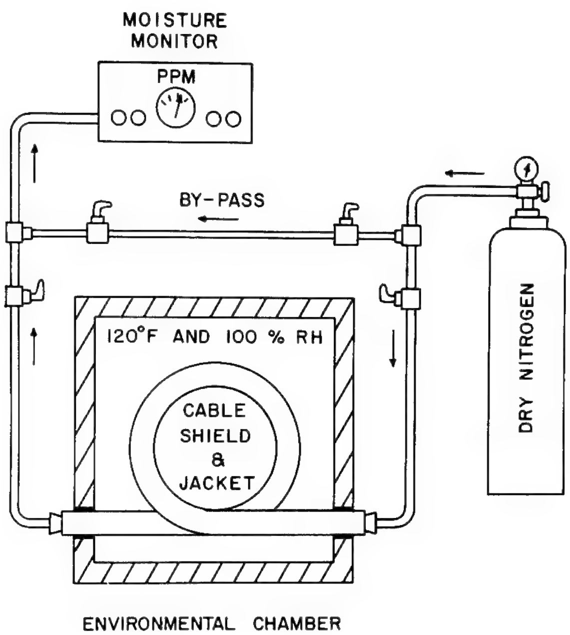

Figure 3 Schematic Drawing of Moisture Permeation Test Equipment

In the experiment, dry nitrogen at a regulated constant flow rate and pressure was passed through the hollow shield and jacket and into a coulometric hygrometer. The reading, corrected for moisture content of the dry nitrogen, indicated the amount of moisture added to the nitrogen by osmotic permeation as it passed through the hollow cable sheath. In less than 13 hours, the rate of moisture permeation went off the hygrometer scale which goes to 1,000 parts per million.

This second experiment has shown that the same basic principle of osmosis demonstrated in the first experiment also applies to this more complex application. It has substantiated that moisture permeates through polyethylene cable jacket by osmotic permeation if there is a differential of vapor pressures and a void under the jacket. In this case, the moisture permeated the polyethylene jacket and then passed through the shield overlap to reach the core area. In comparing these two experiments, the rate of permeation varied only by ratio of polyethylene thickness and effect of temperature differences.

The third experiment has no connection with osmotic permeation but deals with the effect of moisture on electrical characteristics. Twenty feet of a 50 pair, 22 AWG Alpeth Telephone Cable was used for this experiment and varying amounts of moisture were added. The cable was laid out horizontally and water was injected through the jacket and shield at 2 foot intervals with a hypodermic needle. Amounts were added in increments of 0.25 grams per foot. Primary electrical parameters were checked at each increment using test frequencies of 1, 3, 30, 300 and 772 kHz. Since the most significant change in electrical characteristics was found in conductance, this data has been plotted versus amount of water added as shown in Figure 4.

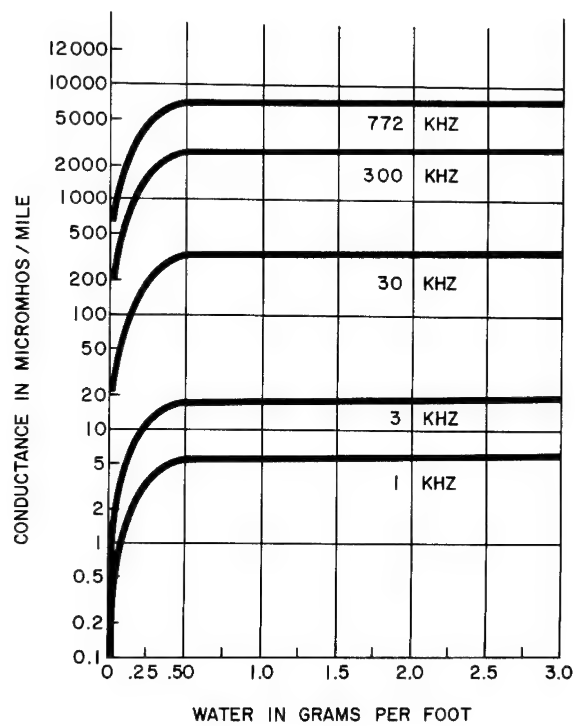

Figure 4 Effects of Moisture on Conductance

In studying the conductance curves, along with mutual capacitance data, it can probably be concluded that small amounts of moisture have insignificant effect at voice frequency transmission. However, at higher frequencies, - especially that of T-1 Carrier at 772 kHz - the effect becomes much more critical. Attenuation at 772 kHz, computed from the primary electrical parameters observed in this experiment, indicated that less than 0.25 grams of water per foot would

produce a PCM bit error rate that would exceed normal acceptable transmission levels.

These experiments have demonstrated the critical factors that must be controlled to provide long-term electrical stability in our telephone cables. This problem has taken on a new degree of urgency with the more sophisticated demands of today's high frequency transmission systems.

Cable Description and Properties

Our answer to this critical problem is a sealed sheath cable design that for all practical purposes provides the same moisture permeation protection as a solid tube. It is an adaptation of a sheathing system developed by Anaconda in 1964 for CATV coaxial cable, which has had an outstanding performance record for moisture permeation resistance. The details of this new construction, which has been designated SEALMETIC®, are shown in Figure 5.

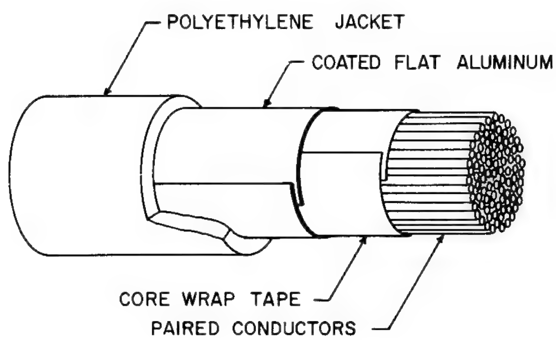

Figure 5 SEALMETIC Cable Construction

The sheathing system uses 8 mil aluminum tape coated on both sides with 2 mils of an acrylic copolymer. This material was developed by Dow Chemical Company several years ago and is marketed under the trade name of Zetabon. The significant characteristics of this copolymer coating are its outstanding adhesion to aluminum plus its ability to bond to itself and to polyethylene jacketing material. In this construction, the coated tape is applied as a smooth (non-corrugated) longitudinal shield with the overlap sealed to make a continuous tube. The polyethylene jacket is then bonded to the smooth aluminum shield which provides a back-up permeation barrier along with several improved physical characteristics.

Since Anaconda and other cable manufacturers have made several versions of bonded aluminum type cables in the past, the significance of this new construction can best be explained by comparison with these other products. The first coated aluminum shield telephone cable in this country was marketed by General Cable and called FPA (Fused Polyethylene Aluminum). The aluminum was coated on both sides to provide corrosion protection so that it could be used in direct burial type cables. In this construction, the natural bonding of the copolymer coating to the outer jacket was purposely limited since the jacket had to be easily stripped from the aluminum for shield termination. Also, there were no requirements placed on sealing the shield overlap. For these reasons, the construction did not have uniform or dependable moisture permeation resistance; but this was not the intent of the product. FPA provided a major breakthrough in the use of aluminum as a shield replacement for copper in direct burial type cables.

The next significant step came with the development of new type shield terminating devices. These systems used penetrating tangs to pierce the shield and did not require separation of the shield and jacket for application. With field acceptance of these terminating devices, Anaconda then introduced a cable with copolymer coated shield that took complete advantage of the outstanding adhesive properties of the coating, since the jacket no longer had to be removed. This cable was specifically designed to reduce moisture permeation and was called MPR (Moisture Permeation Resistant). The construction used the same copolymer coated tape used in FPA cables, but provided maximum bonding rather than limited bonding between the corrugated shield and jacket. This construction made a very significant improvement in the reduction of moisture permeation and has added extensively to the effective life of direct burial cables.

To the development engineer, however, there was still more work to be done because MPR did not provide quite the same degree of moisture permeation resistance that had been accomplished with our bonded coaxial cables. In studying the two products, the reasons for this difference were readily evident. First, while steps were taken to seal the MPR shield at the overlap, it was found impossible to have the tape corrugations always perfectly aligned as required to provide a continuous bond, such as that attained with two flat surfaces. Second, by pull test, it could be easily demonstrated that the same uniformity of adhesion could not be produced in bonding a polyethylene jacket to a corrugated tape as could be provided in bonding a jacket to a smooth tape. While there were serious problems in applying a smooth shield to an irregular, multi-pair telephone cable as compared to the round, uniform coaxial cable, it was concluded that a smooth shield was the only answer to a completely moisture permeation resistant construction.

Now that development of a bonded smooth shield sheathing system has been completed, what have we accomplished? First - consider moisture permeation. Using the same test procedure described under the second experiment of this paper (See Figure 3), the SEALMETIC construction was compared with other cables. In this test, 50 foot samples were again used with the conductors and inner core wrap tape removed. The hollow sheath was placed in an environmental chamber at 100% RH and 120°F to accelerate the

test. Figure 6 shows test results comparing moisture permeation rates for the following cables:

1. 50 pair/22 AWG Alpeth with bare, corrugated aluminum shield and no bonding.

2. 50 pair/22 AWG Alpeth-MPR with coated, corrugated shield and maximum bonding between shield and jacket.

3. 50 pair/22 AWG SEALMETIC with coated, smooth shield, sealed overlap and maximum bonding between shield and jacket.

With cable #1, as discussed earlier in the paper, the moisture permeation rate went to the top of the scale - 1,000 PPM - in about 12 hours. By computation, it was estimated that the permeation rate would reach approximately 2,500 PPM before levelling off. With cable #2, using 50/22 ALP-MPR, the permeation rate went to about 180 PPM in 32 hours. The moisture leakage in this construction resulted from bond imperfections due to the corrugations, as discussed in previous paragraphs. With cable #3, using 50/22 SEALMETIC, the permeation rate stayed at the bottom of the scale with no change in 32 hours. These test results would indicate a moisture barrier ratio of more than 1,000 to 1 for SEALMETIC versus Alpeth type cables.

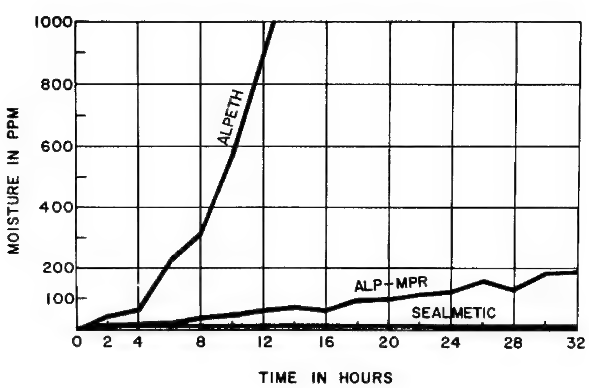

Figure 6 Comparison of Moisture Permeation Rates

Since our goal for this sheath design was to provide stable electrical characteristics, the next test was conducted to check stability. 1,000 foot lengths of both 50/22 Alpeth and 50/22 SEALMETIC cables were used for this test. Each 1,000 foot length was wound on a special reel ~~constructed~~ with slats separating the cable layers so that air could circulate around the entire length. The two reels were placed in our walk-in environmental chamber with the ends extending through portholes for connecting the electrical test equipment. Each cable end was sealed with standard blocking procedures normally used in the field.

This test was run for 30 days at 100% RH with the temperature cycled from 150°F for 16 hours to 140°F for 8 hours. The elevated temperatures were used to accelerate the test and the cycling to represent a very modest day to night temperature change. Electrical characteristics were checked daily and Figure 7 shows the mutual conductance changes for both cables at 1 kHz. As can be readily seen, the SEALMETIC cable showed complete stability while the Alpeth cable showed a continued increase as the moisture permeated through the jacket. The test was terminated after 30 days since there was no indication of any change in the SEALMETIC sheath cable.

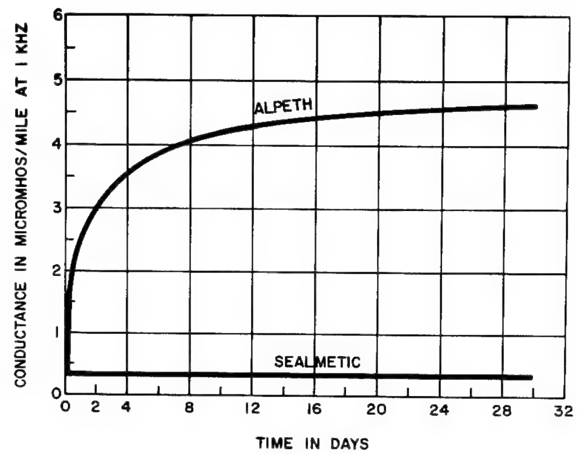

Figure 7 Effects of Moisture Permeation on Conductance

Besides the outstanding moisture barrier provided by the flat shield sheathing system, this construction also has some other interesting physical characteristics. Probably the most surprising of these is the bending properties of the cable which can best be explained by describing a test made in the laboratory. In this test, a 200/22 SEALMETIC cable was bent around a mandrel 8 times the diameter over the jacket to REA bend test requirements. The bend, as required in this test, was first made with the shield overlap away from the mandrel. The cable was then rotated 180° and the bend was made again, which constitutes one cycle per the specification.

The cable was next rotated 90° and the two bends were again repeated for a second cycle. This test was continued for twenty cycles and the shield and jacket slit in half to check the shield condition. At the end of 20 cycles there were no signs of buckling, kinking, or cracking of the shield with the SEALMETIC cable. Exactly the same test was performed on a 200/22 Alpeth cable without shield bonding. When the sample was slit for inspection, the shield was in a series of short pieces. Figure 8 shows the two

shields at the completion of the 20 cycles described.

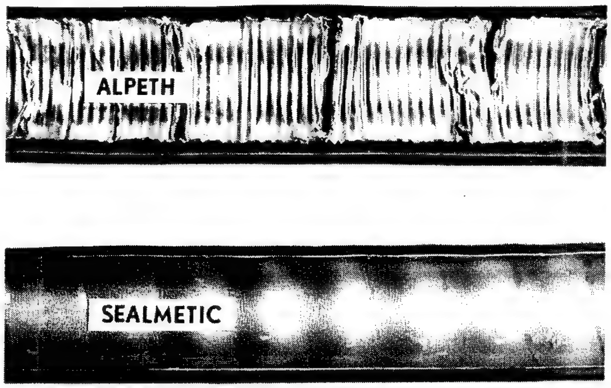

Figure 8 Specimens After Cable Bend Test

Why is the SEALMETIC sheath so much better - it has to be credited to the synergistic effect of the combined sandwich materials. If a strip of bare aluminum is bent double upon itself several times, the strip will first kink and then crack. With a laminate construction of coated aluminum bonded to jacketing material, the same bends can be made many, many times without kinking and cracking. The reason for this difference is because the jacketing material actually supports the weaker aluminum shielding and gives it added strength.

Besides providing this improved bending characteristic, the sealed tube creates a cross sectional hoop effect which also gives added strength. When the aluminum tape is bonded at the overlap, it becomes a structural tube rather than just a wrap of tape. The sealed tube plus the laminated jacket tube provides a structure that will distribute externally applied forces and thus take much more abuse in many of the field applications.

Another interesting advantage of the smooth shield cable is that many of the normal internal jacket stresses have been avoided. In applying a jacket over a corrugated shield, the jacket tube is first formed slightly larger than the shielded core. After it leaves the extruder head, the tube is drawn down onto the shield and into the corrugations by a vacuum. This procedure of re-forming the tube into the irregular configuration of the corrugations leaves a multitude of residual stresses in the finished jacket. With the SEALMETIC sheath, however, the tube is only drawn down tight onto the smooth shield surface. This, quite obviously, does not create the same stress and strain points developed by re-forming the jacket around the irregular corrugated surfaces.

Another area of reduced stresses also occurs within the aluminum shielding material. When the corrugations are formed by running the aluminum through matching gearlike rolls, the tape is work hardened at pressure points which results in irregular areas of strain. Since SEALMETIC uses flat aluminum tape, the stress points produced by the corrugating operation have never been created.

One more area of improvement with the SEALMETIC sheathing system is resistance to cold impact. Tests on 200 pair 22 AWG cables were run at -50°C with the REA cold impact procedure. This requires conditioning of the samples and test equipment for 4 hours at the test temperature and then dropping a one pound weight from three feet onto the jacketed cable. The sample fails if there is any visible cracking of the jacket. In testing SEALMETIC sheath cable, there was 1 failure in 10 samples. With similar size Alpeth cable (corrugated and non-bonded) there were 10 failures in 10 samples. While this test was made under extremely severe conditions of -50°C rather than the REA requirement of -30°C, it does provide another key indicator of stresses built into a corrugated shield jacket.

When development work was started on bonded, smooth shield cable, the goal was to prevent the deterioration of electrical characteristics caused by moisture permeation. Extensive testing indicates that such a moisture barrier has been provided with major improvements coming from the continuous seal at the tape overlap, and the more uniform bond of the smooth shield to the jacket. The advantages in physical characteristics were a plus feature over the original goal, but now offer important additional advantages that stand on their own merit. The SEALMETIC sheathing system is especially recommended for use whereever stabilized conditions are essential.

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A LAMINATE SHEATHED TELEPHONE CABLE WITH A NEW ADHESIVE LAYER

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Abstract

This paper describes a laminate sheathed telephone cable with a new adhesive layer between the polyethylene jacket and the aluminum tape. The adhesive is a ternary copolymer comprised of ethylene, glycidylmethacrylate and vinyl acetate, and has good bond strength to both the polyethylene jacket and the aluminum tape. This cable exhibits excellent properties of fatigue resistance during bending and prevention of moisture permeation.

From aging test data on the adhesive strength between the polyethylene jacket and the aluminum tape in finished cables, it can be predicted that the laminate sheathed cable with the new laminate tape should have a long service life. (Patent pending).

1. Introduction

The laminate sheathed cable is produced by first applying a plastic coated aluminum tape longitudinally over the cable core followed by heat sealing of the overlap seam. Then black pigmented polyethylene is extruded as a jacket over the taped core. The cable is characterized by having a unitized sheath of polyethylene and aluminum tape.

This type of cable has been used widely in many fields because the sheath forms an excellent moisture barrier and has good mechanical characteristics. In order to provide such properties, the aluminum tape must be firmly bonded to the polyethylene jacket by means of an adhesive layer and the overlap of the tape must be fully sealed. The adhesive layer, therefore, plays an important role in the construction of the cable, and must have a high bond strength both to the polyethylene jacket and to the aluminum tape.

Many commercially available resins such as polyethylene[1], ethylene-vinyl acetate copolymer (EVA), ethylene-ethyl acrylate copolymer (EEA), acid copolymer, etc., have already been used in the cable as an adhesive layer. None of these resins, however, provide satisfactory adhesion both to the polyethylene jacket and the aluminum tape. An acid copolymer, for instance, strongly adheres to the aluminum tape but not to the polyethylene jacket. EVA copolymer and polyethylene, conversely, adhere well to the polyethylene jacket but not to the aluminum tape.

In solving this problem, a laminate tape has been used with double layers of an acid copolymer and an EVA copolymer coated on one side of the aluminum tape. The acid copolymer is sandwiched between the aluminum tape and the EVA copolymer in this construction. The use of this tape results in increasing the bond strength between the polyethylene jacket and the aluminum tape and improving the mechanical characteristics of the cable sheath. This laminate tape, however, has a defect in that the overlap can not be sealed firmly due to the poor strength of the aluminum/ethylene-vinyl acetate bond. Also, its complicated double coating construction is expensive, resulting in an increase in cable costs.

Development of a laminate tape with lower costs and higher adhesive strength, therefore, has been required. This has been accomplished by the authors through the successful development of a new adhesive resin for the laminate tape in co-operation with the Sumitomo Chemical Company, Ltd. The telephone cable using this new laminate tape shows excellent properties and is satisfactory in its economics.

2. Properties of the new adhesive resin

Eight adhesive resins shown in Table 1 were examined for the application. These resins were studied for the properties required in a laminate tape, ie. good bond strength to the polyethylene jacket and to the aluminum tape, and satisfactory thermal and flow properties for lamination. The most suitable resin for the adhesive layer was finally selected on the basis of test results from experimentally produced cables.

The new adhesive resin is a ternary copolymer consisting of ethylene, glycidylmethacrylate and vinyl acetate, and is characterized by having good adhesive strength both to the aluminum tape and the polyethylene jacket due to the presence of a reactive epoxy group. Typical properties of the new resin are shown in Table 2. This resin is sold commercially by the Sumitomo Chemical Company, Ltd. with the trade name Bondfast A®.

Table 1. Adhesive Resin

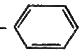
Binary Copolymer		Ternary Copolymer	
Chemical Composition	Active Group	Chemical Composition	Active Group
ethylene-styrene	— 	ethylene -Allylglycidylether -methylacrylate	$-CH-CH_2$ O and$-COOCH_3$
ethylene -glycidylmethacrylate	$-CH-CH_2$ O	ethylene -glycidylacrylate -ethylacrylate	$-CH-CH_2$ O and$-COOC_2H_5$
ethylene -hydrolyzed allylidenacetate	$-CHO$	ethylene -glycidylmethacrylate -methylacrylate	$-CH-CH_2$ O and$-COOCH_3$
ethylene -dimethylaminoethylacrylate	$-N\langle^{CH_3}_{CH_3}$	ethylene -glycidylmethacrylate -vinylacetate	$-CH-CH_2$ O and$-OCOCH_3$

Table 2. Typical Physical Properties

Melt Index, at 190°C	g/min.	2.5
Density, at 23°C	g/cm^3	0.935
Tensile Strength	kg/cm^2	200
Elongation	%	700
Low Temperature Brittleness	°C	lower than -73

3. Bonding properties of the new adhesive resin

The bond strength of the resin when applied separately to a polyethylene sheet and to an aluminum tape was tested in comparison with the bond strength of polyethylene and acid copolymer. The results are shown in Table 3 and Table 4.

The separate sheets of polyethylene-adhesive resin and aluminum-adhesive resin, with a thickness of 2mm, were prepared in a hot press at temperatures of 140°C, 170°C, 200°C, and cut into specimens 100mm wide x 150mm long for peeling tests. The thickness of the aluminum tape was 0.2 mm. The tests were performed at a separating speed of 100mm/min.and a peeling angle of 180°.

The data in Table 3 and Table 4 indicated that the use of the new resin as an adhesive layer should result in a high quality laminate sheathed cable and should also make it possible to increase the speed of the sheathing process.

Table 3. Peeling Strength of Polyethylene Sheet and Resin

Press Temperature / Resin	140°C	170°C	200°C
Polyethylene	more than 10kg/cm	more than 10kg/cm	more than 10kg/cm
Acid Copolymer (Surlyn A)	0.8	1.7	2.0
New Resin (Bondfast A)	2.4	more than 10	more than 10

Table 4. Peeling Strength of Aluminum Tape and Resin

Press Temperature / Resin	140°C	170°C	200°C
Polyethylene	less than 0.3kg/cm	less than 0.3kg/cm	less than 0.3kg/cm
Acid Copolymer (Surlyn A)	4.9	8.2	9.0
New Resin (Bondfast A)	3.8	7.5	8.7

Table 5. Properties of Laminate Sheathed Telephone Cables

Laminate Tape \ Properties	(1) Min. Peeling Strength		(2) Number of Bendings when a crack appears in aluminum tape
	between aluminum and polyethylene jacket	between tapes at overlap	
Conventional Tape:			
Polyethylene Layer	0.95 kg/cm	less than 0.30 kg/cm	10 - 15
Acid Copolymer Layer (Surlyn A)	1.85	2.10	20 - 25
Double Layer	3.05	0.50	20 - 35
New Tape (Bondfast A)	2.70	1.90	30 - 35

(1) Peeling strength was measured under the following conditions:

a) Specimens 10mm wide x 150mm long were taken from the completed cable.

b) Jaw separating test speed was 100mm/min.

(2) Bending test was performed at room temperature (25°C) under the following conditions:

a) Bends were made first in one direction and then in the opposite direction, and the number of two-directional bendings were recorded at the time a crack appeared in the aluminum tape.

b) Mandrel radius was 6 times the cable diameter.

4. Production of the new laminate tape

The optimum extrusion temperature for producing the new laminate tape was about 210 - 250°C. If the extrusion temperature fell below 200°C, uniform lamination was difficult. Above 250°C, the resin tended to decompose and crosslink. The problem of thermal degradation was solved by the addition of a small amount of antioxidant. An extrusion temperature of about 20 - 30°C higher was then possible for lamination. When the new resin is extruded at conditions described above, no change in concentration of the reactive epoxy group was observed before and after extrusion.

5. Trial production of cable

5.1 Properties of laminate sheathed telephone cable

The new adhesive layer (Bondfast A®)-aluminum laminate tape was produced under the conditions described in Section 4. Properties of adhesive strength and fatigue resistance during bending are shown in Table 5 for an experimented cable (#26AWG 100 pair, aerial type) made with this tape, and are compared with properties of cables using conventional laminate tapes. This cable was produced at the same sheathing line speed as for Alpeth sheath cables.

Table 5 shows that fatigue resistance during bending of the aluminum tape depends upon the strength of the aluminum tape-polyethylene jacket bond. Low bond strength causes early separation of the aluminum tape from the polyethylene jacket.

The cable using a double layer tape exhibited comparatively satisfactory fatigue resistance during bending. A low peeling strength between the tape at its overlap seam caused wrinkles to appear on the inner aluminum tape. Cracks at the seam were also sometimes observed, resulting in unsatisfactory bending performance. Further experiments showed that in order to prevent wrinkles when using the double layer tape, the heat sealing time must be lengthened by lowering the sheathing speed.

The excellent bending performance of the cable when using the new layer, as shown in Table 5, is the result of a higherly unitized sheath combining the strength of the aluminum tape component with the excellent elongation and fatigue resistance during bending of the polyethylene component. The sheath uniformly distributes the bending stress to avoid mechanical stress concentrations, resulting in the maintenance of good mechanical characteristics in the cable. This is attributed to the fact that the seam of the tape is sealed firmly and the adhesion between the polyethylene jacket and the aluminum tape is of a high level.

Moisture permeation into the cable core has an undesirable effect upon the properties of the cable, and the laminate sheathed telephone cable has exhibited excellent characteristics as a moisture barrier. Table 6 shows moisture permeation data for experimented cables (#26AWG 100 pair, aerial type) in comparison to that for a conventional polyethylene cable. This data indicates that the laminate sheathed cable has excellent moisture barrier properties. Though there is no difference in moisture permeation data between new and standard tapes, it has already been mentioned that the bond strength at the seam plays an important role[2]. Considering the results shown in Table 5, therefore, it can easily be expected that the laminate sheathed telephone cable made of the

new tape has the best characteristics for prevention of moisture permeation.

Table 6. Moisture Permeation Rate (at 60°C water bath)

Sample	Amount of Moisture Permeation
Conventional Sheath Cable	more than 150 ppm
Laminate Sheathed Cable made of the New Tape	less than 1 ppm
Laminate Sheathed Cable made of Standard Tapes	less than 1 ppm

The moisture permeation rate was measured under the following conditions. The cable core was carefully removed from a cable section of 2m length. Metal caps having capillary gas connections were fitted to the test piece. Nitrogen with below 1 ppm of water vapor was then passed through the test piece, which was secured in a water bath with a temperature of 60±1°C, and into a coulometric hygrometer at a rate of 100 mℓ/min. until a steady reading value was obtained.

5.2 Aging properties

Polyethylene jacket-aluminum tape bond strength in experimental cable sheath is plotted against heat aging time in Fig.1 and against water immersion time in Fig.2. The test specimens were aged in an air-oven at 80°C and in a water-bath at 25°C respectively. The size of test specimens and peeling test procedure were the same as those described in Section 5.1. No decrease in bond strength after aging is observed in either Fig.1 or in Fig.2. From this data, it can be predicted that the laminate sheathed cable with the new tape should have a long service life.

6. Conclusion

Development of aluminum tape laminate with an adhesive layer of a new copolymer comprised of ethylene, glycidylmethacrylate and vinyl acetate, has much improved the quality of laminate sheathed telephone cables. Moreover high sheathing speed without sacrificing cable properties is possible with the use of this new laminate tape. Needless to say, this is desirable in cable manufacture.

7. Acknowledgement

The authors wish to express their sincere appreciation to the people of Nippon Telegraph and Telephone Public Corp. for the continual guidance of the development of the laminate sheathed cable, and the authors also wish to express the appreciation to the people of Sumitomo Chemical Company, Ltd. for their collaboration of the new adhesive resin development.

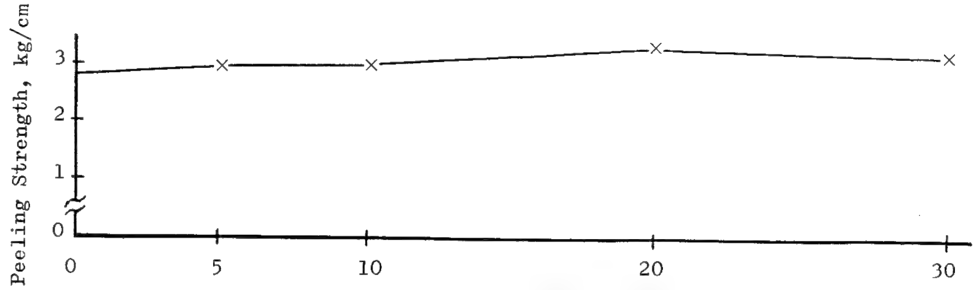


Fig.1 Polyethylene Jacket-Laminate Tape Bond after Heat Aging

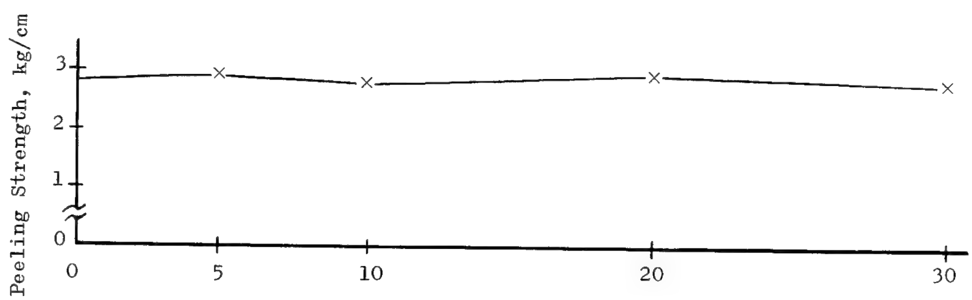


Fig.2 Polyethylene Jacket-Laminate Tape Bond after Water Immersion

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DEVELOPMENT OF NYLON JACKETED TELEPHONE CABLE
RESISTANT TO INSECT ATTACK

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Summary

The field and laboratory testing of the protection against insect attack offered by cables jacketed with nylon are discussed. These tests led to the use of NYLON 11 and NYLON 12. Production problems, cable diameter restrictions, and results of widespread field usage of nylon jacketed cable in Australia over more than five years are described.

Introduction

Insect attack on underground telephone cable, in particular plastic sheathed cable, has been of sufficient economic importance in the Australian Post Office (A.P.O.) network, for a solution to the problem to promise worthwhile savings, and as a consequence of an investigational program dating back to the early 1950's nylon jacketing has been developed and shown to give complete protection. The special problems faced by the A.P.O. due to the vast range of climatic conditions traversed by its telephone network, and the aggressiveness of its termite and ant fauna, have been described in a previous paper to this symposium.[1] At that time (1966) it was concluded that adequate protection of plastic sheathed cable, the sheathing material for underground use in the A.P.O. being polyethylene, could only be provided by a metallic barrier, although some polymeric materials such as nylon and acetal showed sufficient promise to warrant more detailed investigation.

This paper will discuss the test program which led to the adoption of Nylon 11 and 12 as acceptable jacketing materials, and describe the problems encountered in the development of a range of insect resistant cables.

Evaluation of Insect Resistance

Earlier Work

As already mentioned, by 1966 the A.P.O. had established that immunity from termite and ant attack, to the degree considered essential, could be provided by metal tapes or barriers and that some plastic materials used as jackets over the conventional polythene sheath warranted further study. In addition, soil treatment with Dieldrin was meeting with good success in some areas of the country and offered an alternative means of protection. On further consideration, the use of metal tapes was rejected not only on economic grounds, but also because there was concern regarding the possibility of corrosion damage which could still provide the insects with an eventual entry point. There was also some doubt whether soil treatment would give protection over the required 20-40 years of cable life in all climatic environments, particularly in the tropical rainfall areas, but an even more powerful objection was the possible ecological damage which could be caused by treated soils in cultivated or grazing areas and the possible health hazard, mostly due to careless handling, to operating staff.

Nylon 11

Some early tests[2] had shown that Nylon 6 and 6.6 applied as a 0.25 mm jacket, whilst promising, were liable to blister and/or delaminate and that insects could thus gain access to the underlying polythene sheath via cracks in the jacket. It seemed evident that the delamination process was largely due to moisture absorption, and consequently a nylon with much lower moisture absorption properties was required. The optimum material then available was Nylon 11, and hence trial quantities of polythene sheathed cable, with a 0.75 mm thick outer jacket of Nylon 11 were ordered from Australian cable manufacturers. Samples of this cable, together with various other experimental cable constructions, were installed in test plots in the Darwin area from 1964 onwards. In common with most of our previous tests, this program was designed to evaluate the resistance to termite attack, as controlled testing with ants has not met anywhere with much success. However the assumption that any material able to withstand the depredation of the giant termite MASTOTERMES DARWINIENSIS would be able to resist attack by ants, is considered reasonable.

In these tests samples were buried vertically, to a depth of 30-35 cm, in two different types of test plot lay-outs. One was similar to the type used successfully in previous work where the samples, attached to wooden pegs, are arranged in an array of horizontal rows and columns joined by timber laths whose purpose is to lure the termites into the test area. The second type of plot used in the 1964 trials, still retained the pegs and laths arrangement, but these were now arranged in a rough circle around the mound of a termite

species known to attack cables, the theory being that the termites on their normal food gathering excursions would have to pass through, and possibly attack, the sample perimeter (see Fig. 1). Sufficient samples were installed to permit the withdrawal of replicates at roughly yearly intervals for 3 or 4 years. At a later stage of the field trials, some samples of nylon 610 and acetal co-polymer jacketed cables were introduced into some of the test plots.

Laboratory Evaluations

All sample materials were also submitted to the Commonwealth Scientific and Industrial Research Organisation's (C.S.I.R.O.) Division of Entomology, for laboratory evaluation. This organisation has perfected methods which enable the resistance and/or toxicity of materials to be tested against various species of termites under controlled experimental conditions [3] in the laboratory, and in addition they maintain extensive field testing facilities in Northern Queensland where Mastotermes Darwiniensis termites who are not amenable to laboratory conditions, are prevalent.

Test Results

The test program terminated in 1968, and the results [4] made it evident that Nylon 11 provided excellent protection from termite attack, and in fact no damage was recorded with any of the specimens exposed for up to 36 months. The results with acetal co-polymer, though only limited in scale, were also quite promising as were those with Nylon 610, although in the latter case, possibly due to the surface roughness of the experimental samples, there had been some minor, shallow attack. It is interesting to note that the laboratory tests demonstrated that all these materials were liable to damage at the cut ends, where the termites were able to use their mandibles in scissor fashion, but samples where the ends were capped with a metal ferrule did generally escape all attack. This tends to confirm our belief that smoothly extruded sheathing, free of scratches, etc., will always be more difficult for the insects to grip with their mandibles, and that if the material in addition is of reasonable hardness and good resilience, attack is most unlikely. Results obtained with high density polythene, polypropylene, rigid PVC and polyurethane whilst not as good as those for nylon, are far superior to those for low density polythene, plasticised PVC, natural and synthetic rubbers, etc., as would be expected if our theory [5] is valid. At the same time it clearly stresses the importance of proper extrusion conditions, if the advantages gained by the choice of a highly resistant material, are not to be partly sacrificed.

Another field trial was conducted from 1965-1970 on various experimental cable constructions at more than 20 test sites all over the Commonwealth. In these trials, lengths of approximately 50 m were buried at depths of 25 to 50 cm, with one end sealed and the other connected to above ground terminals. Periodic measurements of insulation resistance between conductor and earth were carried out to give indication of damage, and at the end of approximately five years the cables were recovered for detailed examination. It was shown that whilst none of the Nylon 11 jacketed samples had been attacked, there had been several instances of penetration of Nylon 6 jackets. Various other types of plastic materials, with or without additives such as silica, gave poor to moderate results. In the case of brass barriered cables, there was considerable evidence of corrosion even though the insects had not been able to do any damage to the inner plastic sheath. Some cable types performed reasonably well, such as those equipped with greasy barriers or "Tanalith" treated wrappings, but because of their poor physical properties, large size, and the difficulties in handling, they cannot be considered as practical solutions. Our results agree with the findings by other investigators in Australia, in particular the C.S.I.R.O. Division of Entomology, and Nylon 11 has now also been successfully utilised by other authorities in areas where the hazard due to termite or ant attack is high, and steel wire or tape armouring had to be employed previously. Some of this experience now extends over 10 years, without any recorded failure.

Nylon 12 as an Alternative

Nylon 11 is available from only one manufacturer, and in 1969, a worldwide shortage of castor oil, the basic raw material, created a difficult supply position for our ever increasing demand for nylon jacketed, insect proof cable. It therefore became necessary to look for an alternative material and after surveying available materials it was decided to further evaluate Nylon 12. The latter was available from two manufacturers (soon after two further manufacturers entered the market), was made from a readily available petro-chemical, butadiene, and offered a price advantage. Its chemical and physical properties were similar, and with regards to water absorption slightly superior, to Nylon 11. Field and laboratory tests confirmed that Nylon 12 conferred insect resistance equal to Nylon 11, and as a result of several years of testing, two manufacturers' materials have been type approved.

The Effects of Formic Acid

It is well known that a large proportion of the ant family possess venom-producing glands by which they are able to secrete formic acid, as an approximately 50% aqueous solution. For some species it has been calculated that an individual contains up to 2 mg, that is 20% of its total body weight, of formic acid. As formic acid is known to cause some degradation in nylons, experiments were conducted to study the effects of 5% and 50% formic acid solutions on various grades of Nylons. It was shown that Nylons 11 and 12 whilst suffering some decrease in surface hardness, after immersion for up to 28 days at temperatures between 20 and 50°C, were still satisfactory. [6] However, various

other grades such as Nylon 6, 6.6, and 6.10 and also acetal co-polymer were found to suffer severe degradation, and whilst the danger from prolonged exposure to formic acid in service may not be very great, our preference for Nylons 11 or 12 over other nylon materials has been reinforced by these findings.

Manufacturing Problems

General

The problems of placing a thin coating of nylon over a cable sheath take on different aspects depending on whether one is a user interested primarily in the end result or a manufacturer trying to meet the reasonable (or unreasonable?) requirements of a user. The A.P.O. is, as far as cable is concerned, solely a user and therefore the authors of this paper can only give the user's view on the problems and their solution. It is a pity perhaps that we cannot give an adequate coverage of the other side of the story.

Cable Diameters

The initial application of nylon by the A.P.O. was to two-pair cables, less than one centimetre in diameter. The nylon used was a Nylon 6 which had, compared to the other plastics used in cable, a very low melt viscosity and the manufacturers indicated that they did not expect to be able to jacket cables more than $1\frac{1}{2}$ cm in diameter. Restricting the diameter to this low figure would have resulted in a product suitable for use on only about 30% of the sheath length of plastic cable installed in those areas where insect attack could be expected. This percentage was adjudged too low to be acceptable and hence the Australian industry was encouraged to develop its technology towards jacketing of large cables.

The change from Nylon 6 to Nylon 11 which arose from the early trials discussed above, was fortunate as the melt viscosity of the latter is markedly higher and has a low dependence on melt temperature. This led, assisted by better extrusion machinery, to the Australian industry successfully coating cables up to 2 cm in diameter by 1967 and up to 4 cm in diameter shortly after, thereby covering the full diameter range of underground plastic cables for rural areas.

Surface Finish

The laboratory evaluation and field tests included samples that had a surface finish in which small bubble-like imperfections, lumpiness and absence of surface gloss were evident. It was these samples that showed the greatest propensity for being attacked by insects.

The reasons for poor surface finish were investigated, and it was found that the moisture content of the granules entering the extruder was a major factor. A high moisture content lowers the melt viscosity and increases the rate at which the nylon deteriorates (by hydrolysis) at high extruder temperatures.

From the user point of view the problem can be controlled by the inclusion of a specification requirement demanding that the jacket have a smooth glossy surface, free of imperfections, and the A.P.O. specification does include such a requirement. Provision of agreed acceptable and unacceptable samples is useful in determining compliance with this requirement.

This surface finish requirement should provide adequate assurance to the user that jacket defects existing at manufacture will not result in points of weakness which can be attacked by insects. However the A.P.O's specification also limits the moisture content of granules entering the extruder (samples are taken for laboratory evaluation) to a maximum of 0.1%, and limits the time/temperature of the material within the extruder. These requirements are set primarily to guard against other forms of jacket degradation, but they give added security against manufacture of cable with defective jacket.

The aim must be to provide a cable with a "smooth gloss surface" ex factory, but for maximum protection against surface damage during installation by cable ploughing equipment, attention should also be paid to the surface finish and cleanliness of the cable chutes of that equipment. This is desirable but not always achievable. However, no case where minor abrasion of a good "ex factory" jacket has allowed insects to complete the penetration of the jacket has come to our attention.

Cracking of the Jacket

During experimental use of Nylon 12, problems of severe cracking of the jacket during, and even before, installation were reported from a few operating areas. Investigation revealed that all the material involved came from one raw material supplier and from one cable manufacturer. It was found that those samples not yet exhibiting cracks deteriorated rapidly, (within days) on exposure to sunlight. The nylon was said to include some carbon black and an unknown amount of heat stabiliser.

Laboratory investigation of the problem showed:-

(a) The nylon used contained only an insignificant percentage of carbon black.

(b) Test specimens taken from cable immediately after manufacture, exhibited normal tensile strength and elongation properties.

(c) Immediately following manufacture the cables were able to pass a bending test.

(d) Cable aged naturally on cable drums, over about three months during an Australian summer but protected from direct sunlight, sometimes exhibited cracks.

(e) Test specimens taken from cables immediately after manufacture, and artificially aged in a Weatherometer, exhibited embrittlement after periods ranging from 119 to 236 hours.

These results suggested dual causes:-

(a) The nylon had only minimal amounts of heat and light stabilisers incorporated in it.

(b) The temperature and/or time that nylon spent in the extruder during cable manufacture varied and, in some circumstances, e.g., when changing cable size, became excessive so that the stabiliser was largely consumed during the extrusion process.

Concurrently tests by the A.P.O., the cable manufacturers and nylon suppliers confirmed that nylon could be adequately heat and light stabilised, that up to 2% carbon black did not degrade any physical properties of the nylon and aided the stabilisation process, and that factory processing need not exceed certain acceptable temperature/time profiles. Consequently, the A.P.O's specification for Nylon 11 and Nylon 12 for cable jacketing requires the use of heat and light stabilised grades, and carbon black when used as a stabiliser is to comprise 2% by weight. The temperature of the molten resin during extrusion is not permitted to exceed 260°C and the time at that temperature is not to exceed 15 minutes. The time is permitted to double for every 10°C reduction in extrusion temperature. Type approval tests and periodic check tests include tensile stress at yield (median of five tests, to exceed 4,500 lbs/sq. in (3.10×10^7 Pa), elongation at break (median of five tests to exceed 230 per cent) and require that the median observations do not vary by more than 20% after exposure in a Weatherometer to ultraviolet radiation in the range 275-440 nm for 300 hours. The most critical parameter is the elongation. The 20% variation permitted may seem excessive but the thermal environment of the Weatherometer, (temperature 45°-50°C) leads to changes in the crystallinity of the specimens and accounts for much of the permitted variation.

The several grades of Nylon 11 and 12 approved for use and complying with the requirements now specified provide complete immunity from cracking problems. It should be noted that the standard installation practices of the A.P.O. do not require, nor permit, nylon jacketed cables to be installed in situations where they are subjected to sunlight.

Wrinkling of Jacket

Nylon jacketed cable must withstand the bending associated with factory processes, culminating in winding onto a despatch drum, and then after a variable period of storage, sometimes in a hot dry climate, it has to withstand unwinding from the drum and passage into and through cable laying equipment. Finally the cable ends are coiled up in the small "pits" used for housing joints. It must withstand these operations without significant degradation of the "smooth gloss surface" which has been shown to be important in maximising the protection the jacket offers against insect attack. Also the jacket must not become wrinkled, as it could then catch in the cable laying plant, and be severely torn.

Initially A.P.O. specifications required the nylon to be at least 0.25 mm thick and to withstand a bending test on a mandrel with a diameter twenty times the cable diameter. After two forward and reverse 360° cycles of bending the jacket had to "remain continuous and undamaged".

Some problems occurred in the field while this specification was operative. The worst of these were found to arise from cable laying machinery where bends sharper than 20 diameters could occur.

Bending a cable around a curve of diameter twenty times that of the cable results in a strain of 5% and this strain is, with Australian laying machinery, imposed in the opposite direction to the strain on the cable during prolonged storage. When allowance is made for some stress relaxation during storage the effective strain during laying may exceed 7%. For Nylon 11 or 12 a 7% strain in a specimen conditioned at 20°C and 65% R.H. leads to a stress level very close to the yield strength. In a cable, where the average R.H. over the days preceding installation may have been well below 65%, and yet the temperature on a cool morning could be as low as 10°C, local yielding of the jacket is likely, particularly at points where the jacket thickness is below average. As the cable straightens as it leaves the cable laying machinery wrinkles can occur which, at best are a point of weakness, and at worst can be torn by the machinery and leave a section of cable unprotected. Unfortunately once these adverse laying conditions are encountered a considerable segment of the sheath along the whole length of the cable will be subject to the same conditions.

The solution to this problem has been to modify laying equipment by increasing the diameter of any surfaces, wheels, etc., which the cable passes over, to increase the minimum acceptable thickness of the jacket by 50% to 0.37 mm, and to require samples subjected to the bending test to exhibit no wrinkling. The minimum barrel diameter of drums has remained at 20 times the cable diameter. The cost increase occasioned by the thicker jacket has not been excessive, since manufacturers are now able to control the thickness and set their operating point closer to the minimum acceptable thickness.

Some work still remains to be done in defining a conditioning treatment for the bending test that will adequately simulate adverse field conditions. Immediately after extrusion the nylon has extremely low moisture content (well below 0.1%) and performs badly in this test, but after being left with its surface wet for some days and then conditioned in a standard 65% R.H. test environment the cable is able to pass the bending test.

Perhaps a complete solution to the problem of wrinkles under severe bending will not be available until manufacturing methods or materials are developed that provide a high strength bond between the underlying polythene and the nylon jacket. This aspect is under investigation.

Field Experience

Fault Reporting Systems

The A.P.O., like most telephone administrations, has a general fault reporting system whereby field staff attending a fault are required to provide a coded fault docket giving details of the fault, the type of construction involved and their opinions of the cause of the fault. In parallel with this system, facility exists for the field supervisory staff to report plant deficiencies.

The general fault reporting system has never indicated a high incidence of faults attributable to insect attack, but in the early years of polyethylene sheathed cable usage, many reports of large scale damage were received from field supervisory staff, even though plastic cable was not used in areas where termites were known to be a major hazard.

The reason for this apparent contradiction provides an interesting sideline to the main theme of this paper. In brief it arises because, in Australia, field staff are permitted to restore an isolated faulty service in buried cable plant by transfering the service to any good spare pair in the cable, and no attempt is made to locate the actual fault. In such cases the cause of failure is not recorded by the reporting system. With our policy of no party-line service, and the expectation that the demand for services will continue to increase over the life of the cable, most newly installed cables are only 20% to 50% occupied. The transfer procedure may be used repeatedly until cable occupancy surveillance shows that most pairs are either occupied or faulty, whereupon a maintenance group, which is largely independent of the local service restoration group, locates the faults and effects restoration. It was reports from the maintenance organisation that drew attention to the alarming incidence of ant attack in the early 1960's. This incidence was sufficient to cause a reversion to high cost lead sheathed cables in many rural areas of Australia.

Acceptance of Nylon Jacketing

The acceptance in the field of nylon jacketed cable as adequate protection against insect attack, has resulted in low cost plastic cable now being considered suitable for subscribers cables for all rural environments in Australia. Reports from field supervisory staff indicate that ant or termite attack on nylon jacketed cable is non-existent, and all faults attributed to insect attack have been found to occur only on the older unprotected cables. The following figures show the trend:-

Year	1966	1969	1971
Faults attributed to Insect Attack	2.058	2,483	3,078
Sheath Mileage of Plastic Cable	30,671	57,436	72,203
Faults per 100 Sheath Miles	6.7	4.3	4.3

Jointing

An attractive feature of nylon jacketing has been its complete compatibility with our standard methods of jointing plastic cable. These methods were developed with insect protection in mind and are based on the use of two rigid P.V.C. mouldings, with field poured epoxide resins providing a mechanical bond between the cable sheath/jacket and one of the mouldings. Rigid P.V.C. is termite resistant and the epoxide resin whilst not immune is in the form of a thick casting so that total penetration is most improbable. The joints are placed underground in small jointing pits.

Some above-ground joints are used in steel posts and whilst not constructed from recognised insect proof materials, attack within the posts has not occurred, probably because the insects tend to prefer underground locations.

Extension to Other Cable Types

Carrier Cables

Single quad, plastic insulated, plastic sheathed, copper tape screened, nylon jacketed cable is already in extensive use in rural areas as a bearer for two 12-channel FDM carrier systems or one 120-channel FDM system. This cable uses 1.27 mm copper conductors and has proved extremely popular and versatile. It has largely replaced multi-pair, paper insulated, lead sheathed carrier cables.

Voice Frequency Minor Trunk (Toll) and Coaxial Cables

These are usually polythene jacketed, lead sheathed cables and provide satisfactory insect resistance in all but the more hazardous areas, where steel tape armouring is used. In these latter areas it is expected that a nylon jacketed, lead sheathed cable will be a satisfactory and cheaper substitute. To date, fully satisfactory bonding (or flooding) compounds to protect against corrosion of the lead under the nylon have not been developed, and as an interim solution a thin polythene jacket followed by a second jacket of nylon is being used. Cables up to 4 cm outside diameter have now been successfully jacketed, and this is not regarded as the upper attainable limit.

It is expected that the lead sheathed, voice frequency cables, which usually are in the size range 20 to 100 pairs and have about 10% of their pairs allocated as future carrier bearers, will ultimately be replaced by plastic insulated, jelly filled, plastic sheathed, nylon jacketed cables. An extensive development programme for this form of cable is in progress.

Costs, Benefits

General Costs

Overall the cables used by the A.P.O. now consume some 300 tonne of nylon per year. The new material and processing cost for the nylon component in completed cable amounts to around $A1,000,000

per annum. This large expenditure must be set against the derived benefits and compared with the costs of alternative solutions.

For individual cables the cost of jacketing ranges from 10-50% of the total cable cost. Currently about 45% of all plastic cable purchases are nylon jacketed, and due to the cost of jacketing and the large conductor size of many rural cables this portion requires about $A7 million of the $A10 million spent annually by the A.P.O. on small size plastic cable.

Benefits

The major benefit achieved by the use of nylon jacketing is not in the elimination of faults. This statement may surprise but it is true.

Before the adoption of nylon jacketing, the fault incidence in plastic cables in some rural areas was so high that required service standards could not be met. Therefore operating districts had to adopt other forms of cable, typically lead sheathed with plastic jacket or steel tape armour. Hence to achieve a real benefit it is necessary that nylon jacketed cables cost less than these lead sheathed cables and yet give comparable, or better, service performance. In fact the purchase of equivalent quantities of lead sheathed cable would cost at least $A2 million more annually than nylon jacketed cables! In addition there are substantial installation cost advantages with nylon jacketed cables.

This analysis could still lead to an incorrect assessment of the benefit if nylon jacketed cables were to be used in areas where the performance of standard plastic cable is adequate. However this would only become a significant factor if over half the nylon jacketed cable were used incorrectly.

Alternative Solutions

To spend $A1 million per year on nylon protection of cables could still not be justified if cheaper solutions were available. One other possible solution subjected to extensive field trial in Australia was brass tape protection. This cable had brass tapes helically applied over the polythene sheath, and held in place by a thin extrusion of polyethylene. The corrosion liability of such a cable, as demonstrated by our field trials, has been already mentioned in an earlier section of this paper. Its cost was much more than nylon but less than cables with lead sheath. Even when allowance is made for some advantages conferred by the metal tape such as protection against a proportion of lightning strikes, the nylon is a preferable solution.

The use of steel tapes over plastic cables is another possible solution as also would be the Western Electric "Stalpeth" sheath but, in Australia, this would not be cheaper than nylon and has therefore not been investigated.

The incorporation of insecticides in the plastic sheath as part of the extrusion process, has been advocated by various manufacturers and designers. In our experience, which covers a substantial number of such compounds in both polythene and P.V.C., none of the insecticides available have given the required degree of protection. The difficulty appears to be that if the insecticide "blooms" rapidly to the sheath surface, it will repel the insects more effectively but its life will be too short, whilst if the blooming rate is slow enough to allow for a 20-40 year life, there is probably insufficient material available at the outer periphery to give adequate protection. In addition the presence of insecticides is an undesirable health hazard to installation and repair staff.

Conclusion

Our experience with Nylon 11 and 12 extends over almost 10 years, and there is no doubt that this form of protection against insect attack has been outstandingly successful. In fact there has not been a single recorded failure, due to penetration by an insect, of cable jacketed with Nylon 11 or 12 and the only faults recorded have been clearly shown as being due to installation damage, manufacturing defects or incorrect choice of the grade of nylon. Having also surmounted the original limitations with regard to cable size and ease of handling, the A.P.O. has now reached the stage where the probability of insect attack on newly installed cable has been reduced to a negligible magnitude, and the faults now recorded as being due to insect attack almost certainly refer only to the older style, unprotected cables still in the ground.

Prospects for Cost Reductions

As with many semi-automated processes, the major cost component in the cost of nylon jacketing cable is the raw material cost of the nylon. It accounts for 60-70% of the jacketing cost and is therefore the area in which the greatest scope exists for cost reductions. However the residual 30-40% could be reduced by the successful operation of tandem extrusion or "piggy-back" extrusion. The Australian cable industry is being encouraged to pursue developments in these areas.

Alternatives to Nylon

Whilst we are therefore in the happy situation of having reached a solution to our problem, we are continuing to search for cheaper alternative jacketing materials. This work has not advanced to a stage where it is possible to reach any firm conclusions, even though there are a number of promising materials in the course of investigation. The major objective of our studies will be to determine what factors make a polymer insect resistant, and it is hoped to achieve this by conducting a large scale factorial experiment, with termites under laboratory conditions. If these experiments are successful, it should then be possible to accurately predict the magnitudes of physical parameters and the concentration of

polymer components and additives, required to confer insect resistance onto a chosen polymeric material, and accordingly "tailor" jacket or sheath materials to our economic and technological needs.

Acknowledgement

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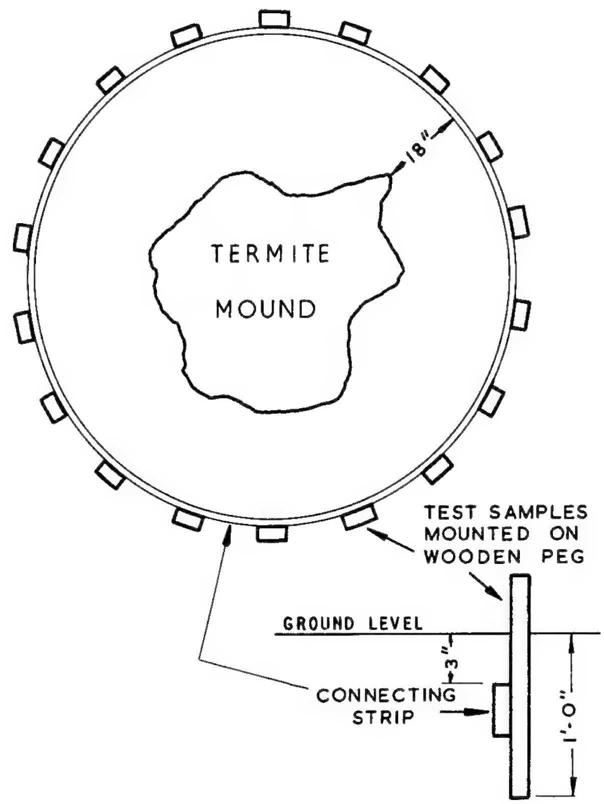

AVERAGE DIAMETER OF PLOT 5' TO 7' DEPENDING ON MOUND DIMENSION. DISTANCE FROM EDGE OF MOUND TO CONNECTING STRIP AT LEAST 18"

FIG. 1 TEST PLOT TYPE 2

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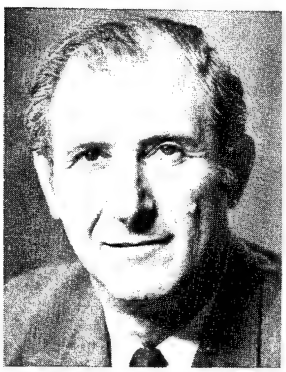

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Mr. Davis joined the Australian Government Public Service in 1939 and, after war service, became an Engineering Cadet with the Australian Post Office and in 1948 Graduated as a Bachelor of Science from the University of Melbourne. After some years in field engineering positions in Tasmania, he transferred to the Lines Branch, Australian Post Office Headquarters where he became responsible for all aspects of plant maintenance and fault clearance. Later he took control of the cable design and provisioning group, a position which he filled during most of the period covered by the development work described in the paper. He is currently the head of the Lines Branch with responsibility for Headquarters aspects of the external plant design and developmental work of the Australian Post Office.

ASCR-ALUMINIUM STEEL COMMUNICATION ROPE

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Summary

For rising need of transmission, the electricity works desire to operate with adequate number of communication channels by means of wires.

The high voltage power line is the usual transmission medium over long distances for electrical energy. For the transmission of communications, it is preferred to use cables fastened to the same high-voltage towers beside the phase conductors.

Problems of extensive spans, mechanical, thermal and electrical requirements of such cables are indicated. Possible solutions in practice are also discussed.

Introduction

Requirements for electrical energy are being doubled every ten years. At the beginning of this century, the electricity works were set up as local or municipal institutions, intended for the supply of power to their own limited areas only. The increase in power requirements called for the establishment of a national network, which is now being extended to international level. The electricity generating power stations, located at great distances from one another, are becoming to an increasing extent dependent upon "on-line coordination". So telephone lines are no longer adequate for this purspose.

The increase in automation necessitates reliable means of transmission lines to control and computing centers. Now that remote-controlled and unmanned transformation and distribution systems have become usual, computers for pre-programming emergency measures and routine switching operations call for even more channels.

Vital data require reliable channels, whereas high data speeds require wideband channels. The growing scarcity of transmission channels makes the introduction of further, efficient transmission media compulsory for many reasons.

All channel requirements can be covered by the use of special aerial cables. Up to the recent these have not been able to enter into competition in high-voltage transmission-line technology, because large spans could only be obtained with high technical resources. The use of new types of material has now made it possible to reach, and even exceed, the maximum possible spans of previous phase conductors with aerial cable constructions.

The development towards ASCR

The necessity for a continuous coordination of the generators and distributors of power amongst each other has shown in the past that specific requirements have arisen for transmission channels in interconnected operation. The items of information to be transmitted are graded in the following sequence of importance:

- Telemetering channels
- Telephone channels
- Protective relaying
- Vital data transmission

Various transmission media have developed in the course of time, differing as to quality, economy and investment costs. The most important of these are discussed briefly in this report.

Buried cables. The simplest medium for the remote transmission of analog or digital control and checking functions is the traditional telephone cable laid in the ground. In core lay, it transmits direct functions without coding terminal devices or multi-utilization devices. We find it nowadays in small systems, mostly as

differential-protection cable in three-core lay, not in pairs or quads.

The situation becomes more confusing for the heavy-current transmission engineer when the demands for a greater number of channels and the extension of his system to hundreds of kilometers, force him to take a leaf out of the book of telephone-cable technology. Complete self-contained telephone installations over multi-paired ground cable systems made it possible for large electricity supply undertakings to get over any number of channels, band widths or distances by the use of direct low-frequency or multiplex relaying.

With ground cables there is an obvious trend towards giving pride of place to safety and simplicity rather than to the optimum transmission technique. Thus, for instance, pupinizing is sometimes rejected eventhough there are long distances to be bridged over. Instead of this, it has long been the custom to use cables in star-quad construction with unusually dimensioned copper-conductors.

Advantageous features are the low temperature coefficient of the attunation, the conventional simple facilities for switching through to public communication systems, the insensitivity to the influence of external radio frequencies and the small chances of disturbance by external ionization noise. One disadvantage is the considerable dependence of the structural layout upon soil conditions e.g. the thickness of the protective armoring against induction. The operators who are accustomed to overhead transmission lines do not take a favourable view of the servicing facilities for a system buried in the ground. The good contact between cables with lead sheath and ground is technically used. Cables which run into areas of risk due to the finite ground contact resistance of a station require special attention in regard to vagabond potential.

There is no question as to whether ground cables are to be regarded as part of the high-voltage system. The distinction from power transmission is perfectly clear.

<u>The power line carrier</u> (PLC) is the transmission technique at present generally used by the E.S.U's. With this method, communications are transmitted over the phase conductors of the high voltage overhead transmission lines. The various channels have carrier frequencies modulated upon them which lie side by side at a set spacing kept as close as possible. The frequency band of 35 - 490 kc is available for this purpose. In the lower frequency range of up to about 140 kc, however, the coupling of the P.L.C. units to the lines is sometimes rather difficult. The reason being the line traps are still relatively low-resistant and the high-voltage-resistant coupling capacitors for the intermediate amplifiers and line transmission equipment cause additional attenuation (2 to 3 dB).

With the asymmetric connection, the CF signals are transmitted in the circuit phase conductor-to-ground. This is a simple arrangement which allows each of the three phase conductors of the high-voltage system to be used separately. However, this arrangement may be unfavorable in the case of difficult ground conditions, because the conductivity of the soil is one of the factors which determine the line attenuation and therefore the range.

With the symmetrical connection there are two alternatives, one being transmission between two different phase conductors and the other, in the case of routes with bundled phase conductors by transmission within one bundle. In the latter case, the various line conductors are insulated against each other over the entire length of the line by insulating spacers.

The line attenuation of the symmetrically operated sections is lower than that of the asymmetrical sections.

A disadvantage of the PLC technique is the fact that the transmission properties of the lines are dependent upon climatic conditions. An undesired increase of the attenuation must be taken into consideration when planning the installations.

Furthermore, the line conductors which hang free and unprotected serve as good antennas for all possible interferences, such as, for example, long wave radio transmitters, corona noise or atmospheric disturbances, so that a relatively high noise level is established on the lines. This must be counteracted by a high reception level at the end of the line in order to ensure an adequate signal-to-noise ratio.

All these dependences result in a considerable curtailment of the range of PLC systems as compared to the theoretical possibilities. The high signal-to-noise ratio also has a direct influence upon the reliability and freedom from interference of the transmission channels, which have to fulfil continually increasing requirements in consequence of the progress of automation and computer-controlled remote monitoring of the power stations and power distribution systems.

It is for this reason that greater importance will be attached in future to other multi-channel transmission methods and media with a greater degree of reliability.

Radio link systems have been used by the ESU's since about 1955 for communication purposes. The advantages of such transmission sections are the high degree of reliability and freedom from interference in addition to the great number of transmissible channels. Furthermore, all the problems connected with the entry into the ground resistance area of the switch plant are done away with, as well as all the safety precautions which have to be taken against overvoltages in the case of wire-bound transmission routes.

These advantages are offset by the very high costs for equipping the sections and also the problems entailed in the allocation of frequency bands. It is precisely the fact that these frequencies are only available to a limited extent which makes it impossible to extend the use of wireless communication between the power stations and the switching plants.

The aerial cables had their origin from ground cables. They are never self-supporting and can only bridge over short distances between poles. According to the purpose they serve, they are suspended on poles and strained to the next pole. The supporting element normally consists of a messenger wire. It is only a few decades before that it has proved possible to fasten standard ground cables continuously during the laying process with the aid of clamps. These aerial cables were a definite technical progress as compared with the bare overhead telephone lines which were suspended on poles and insulated by porcelain insulators.

Self-supporting aerial cables (SAC). Unlike ground cables and aerial cables, the self-supporting aerial cable is continuously submitted to axial tension during operation. Self-supporting aerial cables have a more complicated structure than ordinary cables. Either their cores contain stress-relieved elements in addition to the copper telephone wires, or they have a tension-proof concentric armoring over the cable core. Thin self-supporting aerial cables, sometimes also known as flexible sheathed cables, have been in use for a number of years. The material used for the supporting strain-relieved elements consists of steel, pretreated polyamide and, in recent times, also glass. The following constructions are the most usual (Fig. 1)

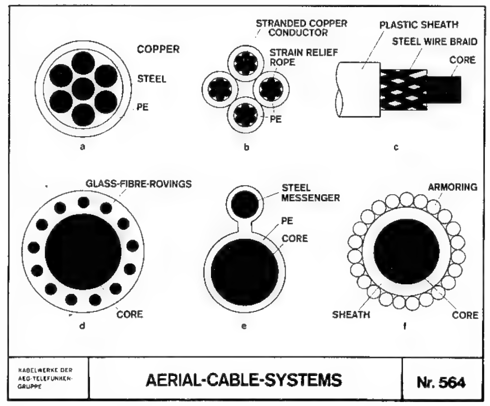

Fig. 1

a) Mixed conductors. Thin copper and steel wires are stranded together to form the cordon of conductors.

b) A separate strain-relief element is provided for each stranded element. Two sheathed strain relief ropes made of steel or polyamide and two insulated stranded copper conductors are brought together to form a star-quad. Supporting elements and copper elements lie diagonally opposite to each other.

c) A concentric braid of flat steel wires over the cable core.

d) Fiberglass rovings embedded in the plastic sheath in the axial direction.

e) Aerial cables in figure-eight form. The supporting cable runs parallel above the cable core and both are covered by a joint extruded outer sheath. The cable cross-section is approximately in the shape of a figure eight.

f) Strain-relief armouring made of round wires applied spirally over the cable sheath.

The versions a) to e) are only used in cases where the poles are closely spaced (preferably less than 100 m). Their structural and manufacturing possibilities are limited. They cannot be used to bridge over such long spans as to enable them to be laid as communication conductors parallel to the phase conductors of overhead power lines.

In Fig. 1, which shows the cross-section diagrams of the self-supporting aerial cables, the last example (f) ist the type which will be dealt with in detail later. It ist made up of the three classical basic elements of cable technology: Cable core, cable sheathing and armoring

This type of cable is becoming increasingly popular because the ESU's operate modern overhead power lines and have laid down the following conditions for the cable makers.

"Self-supporting aerial cables are to be produced which have the same mechanical properties as modern phase and ground conductors for systems up to 380 kV and towers widely spaced at intervals of up to 600 m. The SAC's should not require greater laying and servicing efforts than those usual for phase conductors. It must be possible to transmit a great and extensible number of channels with optimal band widths. The flow of communications may not be impeded by external interference. Ground circuits on the heavy-current side may not endanger either human beings or material on the communications side. Investment and maintenance costs should be below the normal level".

Reasons for the trend towards SAC

The peripheral conditions described above and the requirements of the power transmitters are nothing new. Up to the present the telecommunication objectives have been attained by conventional means, but the tremendous increase in power requirements called for such a number of communication channels as to make the SAC system appear in a favourable economical and technical aspect.

The following motives appear to have caused the increasing popularity of SAC's:

Routing of power lines. In the densely populated areas of western and eastern Europe, special routes have developed for the transportation of energy. In the ground they accommodate high-pressure long-distance gas pipelines, oil pipelines overland water supply systems and cable systems. On the surface we find the long-distance transportation of electricity by means of stepped-up alternating voltages and even already direct voltages (HVDCT 400 kV) by means of high overhead power lines.

This is the optimum arrangement for the power routes regarding rights of way, protection of the amenities and environment, permits, supervisory metering, etc.

Considering, however, that this areas are also traversed by electric rail-borne vehicles with current return conductors in the ground contact, considerable engineering problems arise in connection with guarding against mutual effects. A great number of protective measures are required in regard to corrosion and damage. The "electric interferers" create a sphere of influence several kilometers in width. Attempts are being made to cope with this problem on a legal basis by the establishment of "Arbitration Offices for Electrical Interference". This is usually an expensive solution and from the technical point of view, rather a primitive one. An engineer is the last person who wishes to submit to legal proceedings when he can solve the problems himself by creative means. Protective techniques are lacking in accuracy, in most cases because the soil conditions and the time expectation factor for the inception of interference are in unknown quantities. Over-dimensioning is a frequent consequence.

Aerial cables, on the other hand, are clearly defined in regard to the reduction factor and the grounding conditions. They lie within the sphere of influence of the power supplier and are almost entirely outside the range of third-party interference.

Reduction of the average section lengths. The long-distance transportation of energy runs over power routes. In regional transportation, a trend can be observed towards the reduction in average length, accompanied by the multiplication of high-voltage power lines.

PLC stray interference coupling. The parallel routing of PLC systems gives rise to considerable stray interference coupling between two neighboring lines, which has to be overcome by frequency interlocking. The consequence is lack of frequencies and inadequate facilities for the allocation of urgently needed channels. For similar reasons, radio transmission is usually out of question. Here SAC's can be of assistance.

Costs for coupling equipment. Most transmission media show a tendency towards a rapid rise in the price of coupling equipment. A large proportion of the specific channels costs is already used of before the communication channels has even left the station. Cables are least affected by this adverse factor.

Fault frequency for aerial cables. There is a considerable quantity of statistical material available for ground cables. The fault frequency F is the number of faults per annum in each 100kmeters of cable. Its minimum F = 5 is found in transmission cables laid on special routes away from populous areas. The fault frequency increases to a maximum value of F = 9.9 in districts with unfavourable conditions.

The causes of the faults are also recorded

in the statistics (accidental damage, earth-moving works, lightning, defective points, etc.). Disregarding those faults which cannot occur on aerial cables, we obtain for such cables a fault quota of less than 15% of those for ground cables, that is to say, an absolute figure of less than one fault per annum in each 160 km section. The robust construction and other characteristics, however, make the fault incidence appear even one decade lower. Precise statistical information will be furnished by future experience.

Power-line disturbances account for a fault frequency of only F = 0.012 out of the total value.

Arrangement of the aerial cables in the tower configuration

The weight of the aerial cables imposes an additional load upon the power line towers. Depending upon the type of construction, the weight of the cable core including the necessary moisture barrier is of the order of 500 kgf/km. This corresponds to an additional static load of about 200 kgf with the towers spaced at intervals of 400 m.

Fig. 2 shows the various methods of suspending aerial cables for long spans.

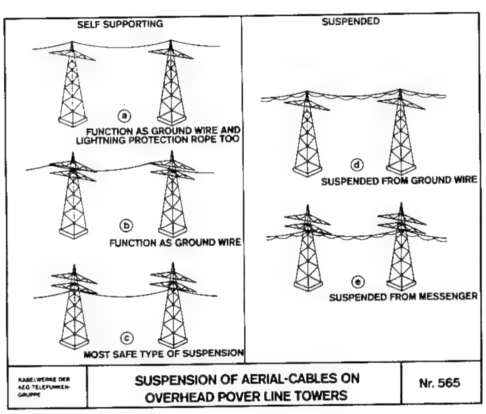

Fig. 2

It is the planing engineer who has to decide whether the costs for an aerial cable communication system should be concentrated on the tower statics or the cable armoring. Either the ground wire or the lightning protection conductor can be used as messenger. The question as to whether one can take the risk of suspending the communication cable on the most exposed point of the tower depends upon the local area of high lightning incidence.

If the system is also expected to transmit vital data and protective relaying, it is advisable to suspend the aerial cable at the safest place, i.e. at the midpoint of the tower, at the level of the lowest phase conductors. There it is most easily accessible for dismantling purposes. Telephone erectors can work here on a platform inside the tower, if, for example capacitor joints have to be made.

Basic structural possibilities

Communications transmission by means of wires make use of symmetrical or asymmetrical line circuits, that is to say, pairs and quads form a contrast to the coaxial pair.

In the case of self-supporting aerial cables too, it was not possible to come to a final decision in favour of either systems. The problems of mechanics and dielectric strength and the necessity to have the repeater sections as long as possible, are the same as those encountered with marine cables. Here also the requirements for the robustness of the construction come to the fore. The expert can see this from the configuration of the cable cross-section.

SAC's, like each cable,are made up of three basic elements, i.e. core, sheathing and mechanical protection.

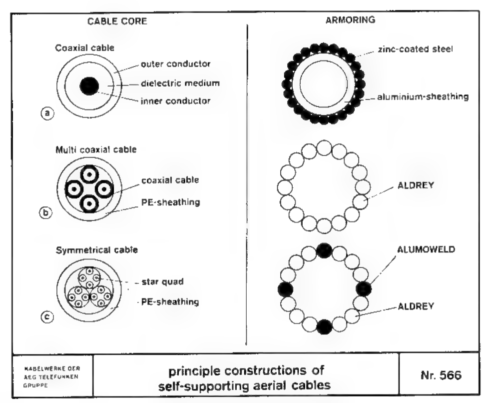

Fig. 3

Fig. 3 shows on the left side (a, b and c) the cores which are at present in general use for SAC's.

The single-coaxial type (a) is robust due to its massive dielectric medium. It does not contain any interstice cavities with air. The outer conductor may consist of metal foil surrounded externally by an extruded plastic sheath.

A more favourable version for the weight of aerial cables is a seamless pressed aluminium sheath which is applied directly on top of the coaxial dielectric medium. This is known as the "Badenwerk type".

This type performs multiple functions such as:

- o Outer conductor
- o Sheath as moisture barrier
- o Low-resistant, light weight element to reduce external interference
- o Transverse stability factor by arching effect (important for mechanically loaded coaxial cables)
- o Highest possible dielectric strength (50 kV), since potential concentration does not occur due to the absence of sharp overlappings
- o High coupling resistance. No bend in the frequency-dependent diagram since there is no seam caused by overlapping

Multicoaxial cable (b) facilitates looping in and out along the aerial cable section. In this case the coaxial pairs are smaller than the single coax pair. They do not possess the same dielectric strength and low line attenuation. The cable sheathing or moisture barrier consists of polyethylene.

Cable cores with symmetrical elements (c) need optimization of the filling factor by the use of star quads. A tentative standard specifies copper conductors of 0.9, 1.2 and 1.4 mm.

The maximum number of star quads used is seven in the case of 0,9 and 1 in the case of 1.4 mm.

Undesirable interstice cavities can be filled up with Polyurethane foam as the lightest filling medium.

The right-hand side of Fig. 3 shows the basic structural methods for the armoring of theSAC's.

The armoring with galvanized steel wires (Fig. 3 d) imparts good supporting properties due to the high tensile strength. But the DC resistance of the armoring is high because of the poor conductivity of the steel. For this reason such cores would not be adequately protected against magnetic influence.

It is therefore essential, when using pure steel-wire armoring, to increase the conductance by arranging a layer with good conductivity below the armoring, as in the case of aluminium sheath (Fig. 3a). In the case of the single coax cables,the aluminium sheath could be identical with the outer conductor. With multicoaxial and symmetrical cables, it is to be applied as a separate element which causes an undesirable increase in the weight of the cable.

As an alternative, it is possible to use an armoring made of aldrey wires (Fig. 3 e) which has good conductivity and thus brings about the necessary reduction of external interference. The aldrey wires, however, have a low tensile strength, so that the carrying capacity of the armoring and with it the attainable span of the aldreyarmored cable is considerably lower.

The optimum construction is shown in Fig. 3 f with a mixed armoring of alumoweld and aldrey. This combination is termed as ASCR where the aldrey wires supply the conductance and the alumoweld wires improve the tensile strength of the armoring. This helps in achieving greater spans and at the same time good protection against external interference.

Alumoweld wires have a steel core and aluminium coating. They are preferred to galvanized steel wires due to reasons discussed later.

The ratio of aldrey to alumoweld wires depends upon the weight and diameter of the cable core and it is given by the required sag characteristics of the SAC's. The cable must be covered as completely as possible by the armoring wires (about 90 to 95%) as an additional condition.

Mechanical parameters. Since the ASCR's are suspended on the same towers as the high voltage lines, one requirement for the mechanical parameters of the aerial cables is that the ASCR's have the same characteristic sag as the phase conductors.

In Germany, it is the practice to use aluminium-steel (Al/St 240/40) as phase conductors. According to German Regulations (VDE 0210), the maximum tensile stress permitted for these phase ropes under the least favourable conditions is 12 kgf/mm^2. With strain lengths of more than 150 m, the least favourable conditions occur at -5°C (23°F) with an additional load of ice. At other temperatures in the considerable range of -20°C (-4°F) to +40°C (104F) the stress is not so high. For safety reasons the ropes are subjected to lower maximum tensile stresses. Values of 7 to 9 kgf/mm^2 are usual.

Allowance is made for the maximum tensile stress to be expected at -5°C (23°F) by suspending the ropes with an appropriate sag. Fig. 4 shows this required sag for the phase ropes with a temperature of +40°C (104°F) as a function of distance between towers.

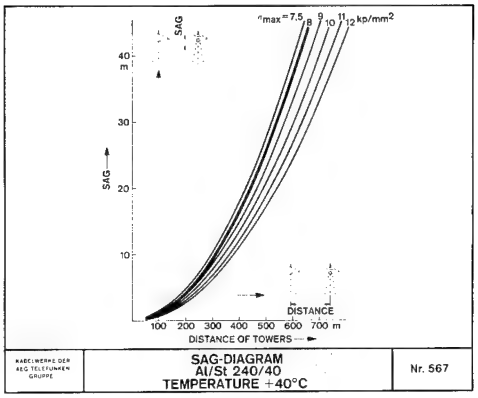

Fig. 4

The thick curve in Fig. 4 for σ_{max}=8kgf/mm^2 is taken as the basis for the following Fig. 5.

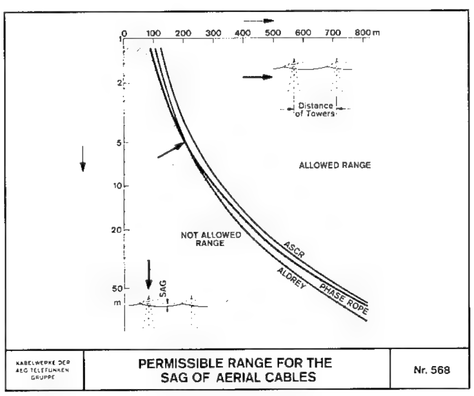

Fig. 5

In addition to the sag curve of the "Phase rope", the sag curve "Aldrey" of a symmetrical aerial cable (armored with 16 aldrey wires and having a core of three star quads) is plotted. The aldrey wires are strained with the maximum tensile stress of 12 kgf/mm^2. The curves intersect at the characteristic point at a tower spacing of about 200 m. If the towers are more closely spaced, the ALDREY-cable may be tauter than the PHASE ROPE without exceeding its maximum tensile stress. By increasing the sag with a corresponding reduction of the tensile stress, it is possible to obtain the same degree of sag for Aldrey cable/Phase rope between 0 - 200 m distance of towers. Above the point of intersection the aerial cable would have to be suspended with a greater sag than the phase conductors, which is not permitted. In this case equality of sag can no longer be obtained.

Pure Aldrey armoring is of advantage from the electrical point of view. For the aerial cable taken as an example it can only be used up to the small span of 200 m. A noticeable improvement can be achieved by substituting alumoweld wires for some of the aldrey armoring wires.

Curve ASCR in Fig. 5 represents the sag characteristic of an ASCR with the same core and a mixed armoring of 4 alumoweld and 12 aldrey wires. Because it remains always above the sag characteristic for the phase rope and never dives into the not allowed range, it can be used in every power-line route for tower spacings of up to 700 m (with the same sag).

The substitution of alumoweld for aldrey wires increases the maximum span obtainable (Fig. 6). By using the alumoweld wires with their better carrying capacity it is possible to raise the limit of the maximum tensile stress for the mixed armoring.

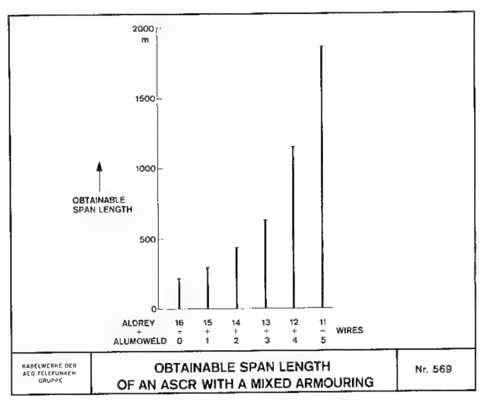

Fig. 6

In the case of the example discussed above with a mixed armoring of 4 alumoweld and 12 aldrey wires, a maximum tensile stress of 19 kgf/mm^2 can be permitted for the armoring. In this case the alumoweld wires, which take up the greater part of the tensile stress, are only stressed up to about 30 kgf/mm^2. This value lies below the reversed bending strength of the alumoweld wires (33kgf/mm^2) as shown in the Wöhler diagram (see Fig. 15). This construction still allows an adequate safety margin with a superimposed bending stress caused by vibration of the cables. The possibilities for

combination between core and carrying structures are so numerous that each special case should be calculated with the aid of existing computer programs.

Standard electric values of SAC. The important electric and transmission values are summarized in Fig. 7. Besides these, there are different types of aerial cables with other special values, such as "Worst Corrected Echo", "Structural Return Loss" etc, not included in this Fig. 7.

The specifications for a single length and connected lines of these systems are voluminous and so here not detailed.

Property	Dimension	Standard electric values of SSAC				
Conductor type		symmetric (starquad)			coaxial pair	
	mm	0,9	1,2	1,4	2,3/10	0,65/2,8
Operated by		DC, impulse pupin loaded, phantom circuit			voice frequency, carrier frequency	
Thickness of the PE-insulation	mm	0,5	0,7	1,3	3,85	0,58
Dielectric strength testing voltage conductor/conductor	kV_{rms}	3			30	3
conductor/earthed sheath	kV_{rms}	20				20
max. working voltage	kV_{rms}	1			5	1
Transient voltage (1,2/50µsec) conductor/earthed sheath	kV	120			>150	100
Thermal nominal short-circuit current	kA	>10			>10	>10
Reduction factor (50 cps)		<0,5			<0,3	<0,5
Loop resistance	Ω/km	56,6	31,8	23,4	4,15	76
Insulation resistance	GΩ·km	>10				
Mutual capacity	nF/km	40			76	51
Impedance	Ω	135			60	75
Crosstalk near-end	dB/km	68			–	145
far-end	dB/km	65			–	132
Line attenuation 0,8 Kc	dB/km	0,6	0,5	0,4	0,25	0,94
0,25 Mc	dB/km	4,1	3,8	2,5	1,76	5,5
0,5 Mc	dB/km	5,9	5,5	3,8	2,46	7,0
1,0 Mc	dB/km	–	–	–	3,47	10,0
Temperature coefficient	%/°C	<0,2				

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Fig. 7

Cable construction. The ASCR's should have approximately the same external diameter and the same mechanical properties as the phase ropes of the power system in order that they can be suspended with the same tools and installation devices. Figs. 8 and 9 show the ASCR types in general use in the Federal Republic of Germany.

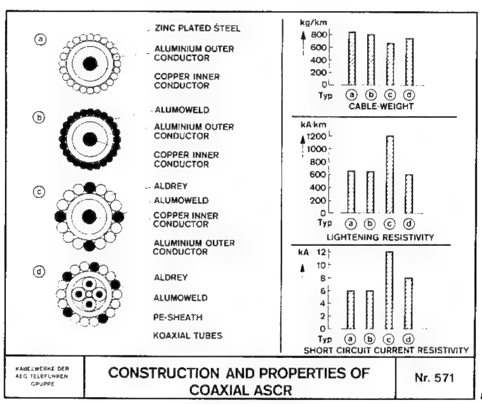

Fig. 8

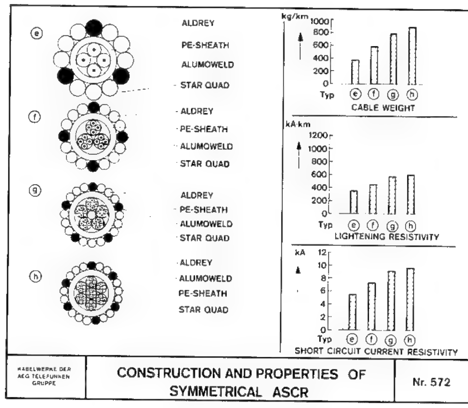

Fig. 9

In consideration of the requirement that the surface of the cable core should be covered as completely as possible by the armoring wires, the armoring of the various coaxial and symmetrical ASCR's is dimensioned so as to produce optimum spans with as low a cable weight as possible. For this reason special attention should be devoted to the weight of the cable, because it enters into the tower statics as additional load and may entail a more complicated tower structure.

With the exception of the coaxial SAC with zinc-steel-wire armoring, which can only be suspended with a sag equal to that of the phase ropes over a span of 600 m, all ASCR constructions mentioned, can be suspended with sag-equality up to spans far exceeding the maximum of 1065 m admissible for the Al/St 240/40 phase ropes.

Problems of external electrical interferences

Various electrical processes in the immediate or more distant vicinity of an aerial cable produce induced voltages in its conductor circuits. These undesirable interference phenomena differ in frequency, duration and intensity. By specific measures they can be calculated in advance, recognized, analyzed and reduced by technical means.

Disturbing currents enter the aerial cable almost exclusively due to magnetic induction, but also to a very slight extent via galvanic coupling when the potential of a station is raised due to the finite grounding resistance in case of a short-circuit. The problem of capacitive coupling no longer exists for aerial cables, since a grounded Faraday

cage (metallic sheathing, armoring) is practically always present. Fig. 10 shows an "Disturbance Analysis" for all imaginable cases of interference.

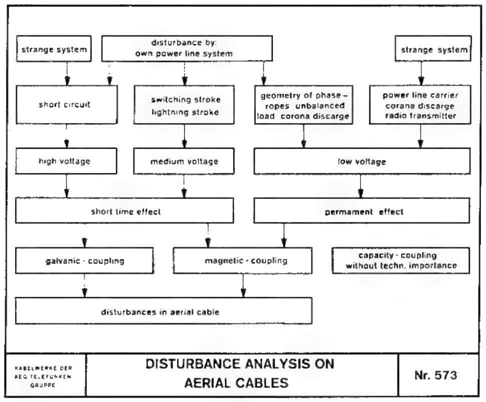

Fig. 10

The "permanent effect" as shown in Fig. 10 as "low voltage" via "magnetic coupling" brings "disturbances in SAC". It emanates either from a "strange system" which causes "corona discharge" or "PLC cross-talk", or from interference by a "radio transmitter". A disturbance by "own system" may be caused by faults in the "geometry of phase ropes" by "unbalanced load" or by "corona discharge".

Technical alternative currents. The inherent frequency (50 or 60 /c/s) of the power line is generally to be found in aerial cables in the form of a voltage which can be continuously measured. Harmonics and thyristor disturbances occur to a limited extent only. The voltage is applied in the "asymmetrical circuit to ground", i.e. with a star quad in the conductor/ armoring system and with a coaxial pair between central and auter conductor. The transmission circuit of a star quad (conductor/conductor is only disturbed if the conductors have different resistances or if capacitive unbalance pair to earth is present.

The asymmetrical permanent voltage is of the order of 2V/50 cps and 2 mV/800cps.

A coaxial cable with an earthed outer conductor carries this hum voltage permanently. It does not usually cause any harm, because the coaxial circuits are multiplexed in the RF spectrum. If, however, the direct audio-frequency range is to be used, the 50 cps hum voltage can be easily short-circuited selectively by switching on parallel resonance.

Permanent monitoring of the insulation (inner-conductor/earth) is possible if a high-ohmic smoothing resistor is interposed.

The corona interference causes a broad-band noise level in a frequency spectrum right up to the radio frequency range. Unfavourable weather conditions bring the noise level to rise by 17 dB. This interference can become a nuisance in aerial cables with a low protection factor. With suitable cables the corona noise level amounts to about -104 dB. It should not fall below -87dB.

External RF interference. The coupling resistance is a criterion for the capability of a cable to reduce external RF interference. If, due to the construction, the protective metal cable sheath has as low a resistance as possible and is amply overlapped, or even seamless, the noise level of external radio transmitters and external PLC circuits can be kept lower than -90dB. The operational value should not be less than -87dB.

Interference pulses. Insulation flash-overs, atmospheric discharges and power circuit breakers give rise to transient waves with steep rising slopes. Due to the mutual inductivity M between power line and aerial cable, a current transformation takes place according to

$$M \cdot \frac{di}{dt}$$

The differentiation process $\frac{di}{dt}$ results in short interference pulses on the communication line. Some of these pulses are of considerable amplitude. Aerial cables with a low protection factor may have such needle pulses of 1000 V in the asymmetrical circuit.

Effects of short-circuits. Whereas the effects hitherto described were merely in the nature of disturbances, induction caused by the complete short-circuiting of a power line is a genuine danger to persons and communication systems.

The highest voltage occurs on a cable conductor/ earth, the "far end" of which is earthed. The magnitude of the dangerous voltage can be calculated in each case with the aid of the formula for inductive interference:

$$E_i = 2 \cdot \pi \cdot f \cdot M \cdot l \cdot I_K \cdot r$$

for example:

f = Frequency = 60 cps

M = Mutual inductance 1 mH/km

l = Length of exposure of aerial cable and power line, e.g. 15 km

I_K = Short circuit current, e.g. 20 kA

r = Reduction factor resulting from cable and system, e.g. 0.5

It thereby follows that:

$$E_i = 33{,}9 \text{ kV}$$

In this case protective measures (see Fig. 11) are absolutely essential and of major importance.

Lightning. Aerial cables are exposed to lightning strokes. This applies particularly to ASCR's laid as a substitute for the overhead earthing conductor.

If lightning strikes an ASCR, the lightning divides up to flow in each direction. It passes over the metallic outer sheath of the ASCR to the towers and from there to the ground.

The lightning current in the metal sheath of the ASCR causes a voltage drop on its inner side. This voltage drop is proportional to the coupling-resistance R_K of the sheath. The insulation in the cable must keep this voltage away from the cable core.

According to Pairitsch, PE-insulations resist nominal impulse-withstand-voltages (U_{St}) of 65 to 70 kV per millimeter of wall thickness.

The criterion for the insensitivity of a cable to the effects of lightning is the "lightning-resisting-factor g". It is defined as the quotient of nominal impulse-withstand-voltage and coupling-resistance.

$$g = \frac{U_{St}}{R_K} \qquad \text{kA} \cdot \text{km}$$

and it should be as high as possible.

It is influenced on the construction side by

- o Increasing the dielectric strength core/metal sheath
- o Selection of a metal sheath which does not permit the lightning current to penetrate inside it, i.e. a sheath with low R_K.

The coupling resistance is not identical with the DC resistance of the cable sheath. It depends upon the structure of the outer metallic covering of a cable.

With flat aluminium sheaths it is about 0.5 to 0.9 times the value of the DC resistance. If the metallic covering of the cable sheath consists of aluminium wires which are in contact with each other, the coupling resistance is about five times as high as the DC resistance. With an armoring made of flat galvanized iron wires, the coupling resistance and the DC resistance are equal. The value of 0.5 times to twice the DC resistance was measured on an aluminium sheath covered with flat iron wire.

Lightning strokes should not leave any traces of melting on the armoring wires, since these would weaken the armoring wires. In the case of an armoring wire which is composed of two kinds of metal, e.g. alumoweld, the aluminium as an outer layer may be damaged right down to the iron core. This would lead to corosion.

No melting traces are found when the armoring consists of material with good conductivity, such as aluminium or aldrey. The danger is then similar to that for steel aluminium cables. Many years of experience have shown that no damage has occured to cables where the diameter of the individual wires was greater than 2.5 mm.

Protective methods and devices for cable systems, exposed to the effects of external currents, will be found in many publications. For use with aerial cables, however, most of these methods have to be adapted to the more difficult conditions, which are, however, more clearly visible.

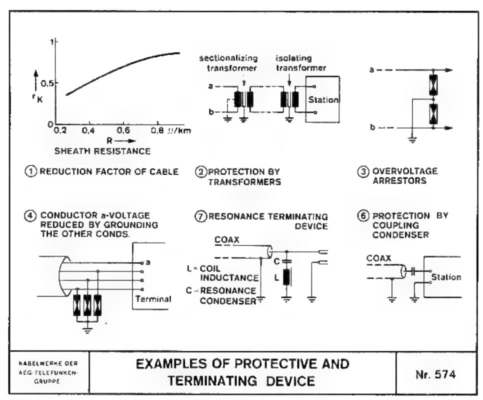

Fig. 11

Structural measures for cables

Increasing the reduction factor (r_K, Fig. 11, item 1) of the aerial cable is a conventional measure, for which the following formula is used:

$$r_K = \frac{R}{\sqrt{R^2 + (\omega L)^2}}$$

R = sheath resistance

L = longitudinal sheath inductivity

Unfortunately, the iron core in alumoweld wires does not effectively increase the longitudinal inductivity. The only choise therefore is to reduce the sheath resistance R by increasing the aluminium conductor cross-section.

The dielectric strength of cable-core/metallic covering is increased by the use of modern plastics.

The thermal stability of the PE insulation when the metal sheath is stressed by short-circuit currents must be guaranteed.

Fig. 12

This is attained by structural measures and determined according to VDE Specification 0103 as "thermal short-time current I_{th} kA" a function of time and ambient temperature. For example: at an ambient temperature of 20°C (68°F), the thermal short-time current I_{th}=8kA, after a duration of 1.4 sec produces a temperature of 120°C (248°F) on the PE surface of the core. Fig. 12 shows a cable which has been too highly stressed by thermal overcurrent.

Protective measures on the system
The earth-contact-resistance of towers and stations is a component of the resultant reduction factor.

Sectionalizing transformers and overvoltage arrestors are generally used with a variety of switching devices and combinations between them (Fig. 11, items 2 and 3).
To save costs, the coupling condenser used for PLC, can be taken with a lower dielectric strength. It does not have voltage continuously applied, since it is only loaded when a short-circuit actually occurs (Fig. 11, item 6).

The resonance circuit (Fig. 11, item 5) is a relatively new, but tested element which reduces constant voltage. It is tuned to the fundamental frequency only, whereas reduction transformers also reduce the harmonics interference spectrum. An arrangement according to Fig. 11 item 4 has the same effect as an additional earth conductor. In this case a short-circuit ignites the gas-filled overvoltage arrestors, which earth the unimportant cable conductors in the same way as an additional earth conductor. The vital conductor (a) is not earthed in its operational state, but its interference voltage is partially reduced.

Laying and installation

The laying process constitutes a maximum stress for the aerial cable. Both the heavy braking winch on the ground and the pulleys high up on the tower exert a strong transverse pressure on the cable. This punctiform pressure is transmitted into the axial direction leading to the cable core.

The length of lay of the armoring and the diameters of cable core and armoring wires are matched to each other in such a way that, under the influence of the axial traction force, the round wires give each other mutual support and do not slide over but they form a vault in which the cable core lies. If uncontrolled radial stresses occur, the dielectric strength, the return loss etc. deteriorate.

The draw-in force in the longitudinal direction present no problems for an ASCR. Nowaday, cables can be manufactured in lengths of 4 km, whereby it does not usually happen that one wire of the armoring is welded.

Strain fittings. Fig. 13 shows a straining spiral with a bifurcated clevis thimble corresponding to the system used by the Preformed Line Products Company, Cleveland. This straining spiral works on the same priciple as a cable grip. In the slack state the straining spirals are wound around the armoring of the aerial cable in such a way that their inner side, which is coated with hard crystals, presses against the ASCR. The straining spirals and the cable armoring must have the same direction of twist.

Connection joints. In the case of aerial cables for short spans, it is possible to splice the end of one cable to the beginning of the next on the ground and then to pull up and strain the splice with the cable. Aerial cables with symmetrical and coaxial transmission elements are preferable connected to one another in dome jointings boxes which are fastened to the tower (Fig. 13). This kind of jointing is preferred if it is desired to have the joint boxes available

for inspection, or for the entries of switching elements (overvoltage arrestors, etc.).

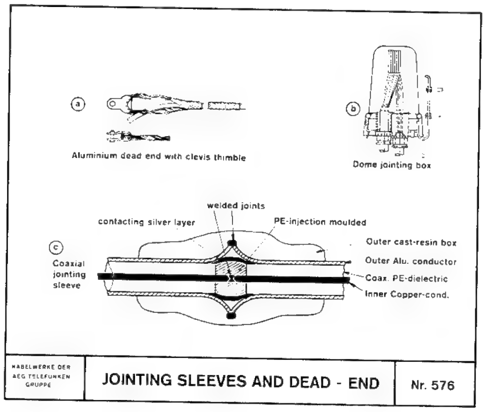

Fig. 13

A cigar-shaped coaxial joint box (Fig. 13 c), is used for high-voltage-proof coaxial cables (30 kV) which do not require to be subdivided by sectionalizing transformers into short sections in order to save hazardous influence. The special feature of this joint box is that the welded joint of the inner conductors is enclosed in a seamless, injection-moulded PE. The outer conductor encloses the welded joint concentrically. After the outer conductors have been welded, the entire fitting is enclosed in a NOVERIN - "cast-resin case". This concession to additional installation effort must be made in all cases where return loss, high dielectric strength and absolute durability are required.

Transmission systems. In principle, all the transmission systems known and well proven on cable lines, can also be used for aerial cables. There is, fortunately, no necessity for the design of basically new systems. All the transmission systems in use must, however, be modified at the junction points of ASCR/equipment-units and must be adapted to the special requirements of aerial cables.

In PLC systems Z 12, it is possible to bridge over a line loss of 6 N = 52 dB, or even 8 N = 69.5 dB when using high-level PLC-transmitters.

The maximum ranges in km with cables according to Fig. 7 may amount to:

conductor diameter	at 108 kc/s 52 dB	69.5 dB	at 800 c/s 26 dB
symmetrical			
0.9 mm	19 km	25 km	43 km
1.2 mm	23 km	31 km	52 km
1.4 mm	33 km	44 km	65 km
coaxial			
2.3 /10	44 km	59 km	104 km
0.65/2.8	14 km	19 km	28 km

Standard repeater sections of 30 or 40 km are recommended for symmetrical cables.

Aerial cables are suited for operation with those PLC systems with which the ESU's are well acquainted. With the gradual introduction of aerial cable systems it is thus quite possible (from the economical point of view) to integrate them in existing systems.

Both double side-band transmission and the technically more elaborate single side-band transmission are possible. With regard to the number of channels, the latter permits double the utilization of the given frequency band. The ASCR are also suited for equipment with digital systems, i.e. with PCM and Videophone. The coaxial ASCR's in particular can be operated with digital systems having high bit rates, due to their broad bandwidth.

Long-distance communications. Up to the present there has only been mention of transmission by aerial cables within regional areas. The physical distance of electric transmission media is limited by the line loss. Each audio-frequency and radio-frequency signal has to be regenerated in repeater sections. Long-distance communication systems are build up by lining up repeater sections.

This is also basically feasible with ASCR, but in this case there are additional problems to be overcome.

- o Temperature differences of -40°C (-40°F) to +60°C (140°F). These cause fluctuations of the receiving level by variations in the line loss. The amplifiers must possess a wide, automatic control range with a short time-constant (day-night).
- o Voltage supply to the intermediate amplifiers
- o Connecting a line into a ASCR (Loop-in) Looping in and out within the repeater sections is more difficult than in the case of ground cables, particularly if other conductors of the line than

the looped-in are to run through. Specially with symmetrical transmission elements in the cable, the problems posed by higher transmission level occur, whereas with coaxial elements the difference in levels is easier to deal with..Switching elements involve additional losses.

o Crosstalk balancing for symmetrical cables
Star quads are used in order to keep the weight as low as possible. Cable technology can offer a crosstalk attenuation of max. 61 dB (i.e., 7Neper) without balancing.

For long-distance communications systems, however, using additional measures, this value must be brought to 71 dB (i.e. 8.2 Np). Transpositing equalization is not always adequate, so balancing by condensers in every repeater section becomes necessary.

Due to the specific problems associated with aerial cables, the balancing condensers can no longer be accomodated by the conventional method of single mounting in condenser boxes during the balancing measurements. Plug-in units (Fig. 14), already equipped with special condensers, can be plugged into a condenser-box at the top of the tower in a short time.

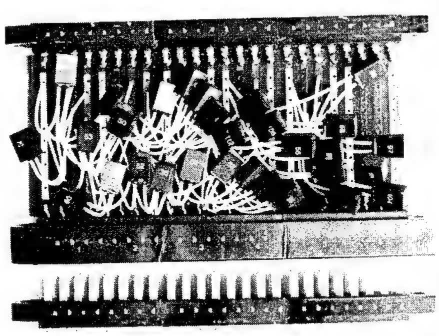

Fig. 14

The plug-in units are connected by T-splicing, that is to say, without additional soldering points in the current path.

The condensers are suited for high temperatures and they have a low temperature coefficient. This keeps the capacitive balancing efficient inspite of varying temperature cycles. They were developed by ROSENTHAL.

External dynamic influences. Up to here, the span, and sag of SAC's were calculated on the basis of static properties. Behavior under dynamic stress must, however, also be considered. The fittings were designed with the object of damping the vibrations of the self-supporting aerial cable. Tests were carried out on cables to determine the dynamic behavior of the wires selected for the armoring. The Wöhler-Diagram, Fig. 15, gives information on this property.

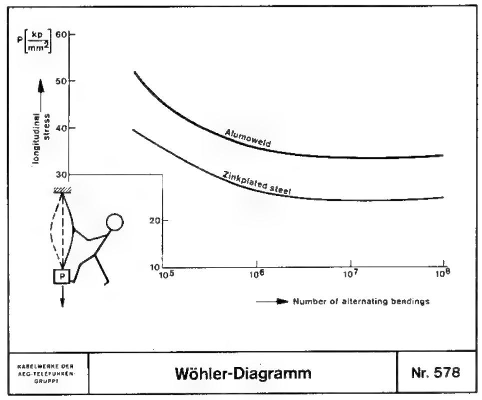

Fig. 15

It can be seen how many alternating bends a wire will withstand when a static longitudinal stress is applied. According to the manufacturers, this static prestressing with over 10^7 alternating bends gives the following data:

for alumoweld	greater than 33 kgf/mm^2
for galvanized steel wires	greater than 25 kgf/mm^2

Alumoweld wires are not as sensitive to vibration as galvanized steel wires.

Effects of the weather. Aerial cables are particularly exposed to changes in temperature. The effects of temperature change on the armoring, and thus on strain length and sag, have already been mentioned.

The electrical properties also change with the temperature. For the self-supporting aerial cable 2Y2Yb, 6x2x0.9, the temperature coefficient of the line loss has been accurately measured on a cable 4 km in length. The measured temperatures were recorded from -10°C (14°F) to +51°C (124°F) (Fig. 16).

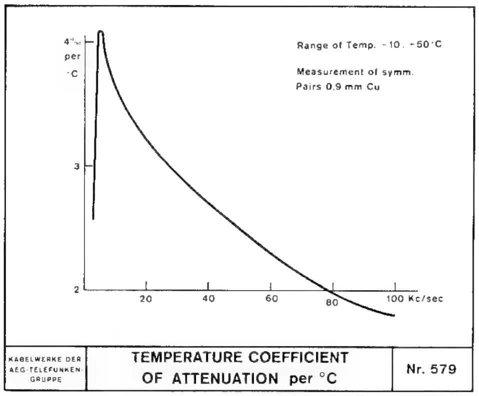

Fig. 16

Attention must be paid to the diffusion of atmospheric moisture into cables with interstices inside the core. The moisture may penetrate through the polyethylene sheath.

According to Fick's first law of diffusion the quantity of moisture, penetrating into the cable core is proportinal to:

- the surface of the PE sheath
- the pressure gradients of the partial pressure
- the diffusion constants
- the time,

and is inversely proportional to the thickness of the sheath.

The penetration of water is due to the "pumping effect" of an aerial cable. This occurs as a result of sonsiderable temperature changes at short intervals. When the temperature falls below dew point, moist air which has penetrated or pumped into the cable condenses to water and it is possible that water pockets result at the lowest points of all sags.

These faults can be prevented using suitable cable constructions (metallic water-barriers), avoiding interstices in the cable core (coaxial cable or polyrethane foam filling) and watertight cable junction-boxes. The insulation of the conductors themselves are immune to reductions of insulation, since they have thick walls, but digital transmission will find reflection-faults and impedance-resonance.

We should further consider what happens to the armoring wires in the free atmosphere.

It is a known fact that steel-aluminium phase ropes have a long service life, and the same can be expected of aerial cables with uniform armoring if it consists exclusively of aluminium, aldrey or alumoweld wires. In this case the electrolytic formation of elements does not take place. The liability to chemical reaction is the same for all three above-mentioned metals and metal alloys.

Electrolytic element formation is only to be feared if the zinc coating of galvanized steel wires or the aluminium coating of alumoweld wires is badly damaged. The zinc coating is the more delicate of the two. Fig. 17 shows an enlarged cross-section of the various zones of a galvanized steel wire.

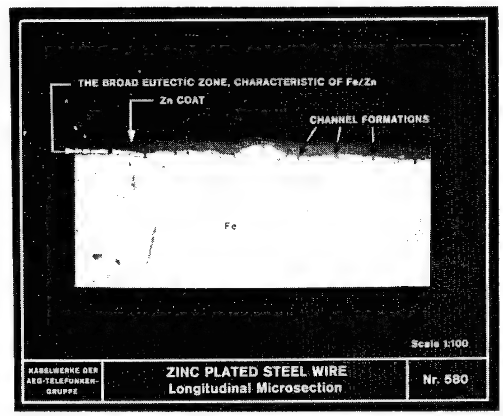

Fig. 17

The typical thick, porous, iron-zinc alloy eutectic zone lies in between the steel (Fe) and the zinc-coat and harms the adhesion of the zinc layer. Damage to the zinc coating is, however, normally not so serious, because zinc is more electro negative than iron. In the potential scale the value of oxydized aluminium lies in the same range as zinc (-0.77 V).

The barrier layer between aluminium and iron is much thinner than that between zinc and iron and cannot be optically measured. Even the electronic microscope shows no eutectic zone (Fig. 18) as shown in case of Fe/Zn (Fig. 17).

The coatings of the wires must adhere well so that they do not spring off during the cables production and laying process. For this reason the wires are subjected to bending tests (Fig. 19).

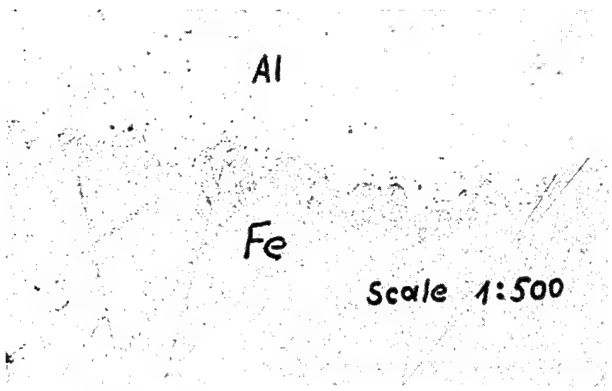

Fig. 18

Fig. 19

The surfaces of both galvanized steel wires (A) and alumoweld wires (B) remain free from cracks if the test wires are wound into a spike with three times the diameter of the wire (top of diagram). If, on the other hand, the wires are wound around spikes having a diameter equal to that of the wire, cracks appear in the zinc coating, as shown in Fig. 20.

Fig. 20

These cracks are, however, not present in alumoweld wires.

The wire coatings are tested even more severely in the so-called "torsion test". In these tests the single wire with one end fixed is turned on its axis until cracks appear on the surface. The number of turns required until the cracks occur is a criterion for the quality of the coating adhesion. With alumoweld wires the steel core broke before the aluminium surface showed signs of cracking. (Fig.21)

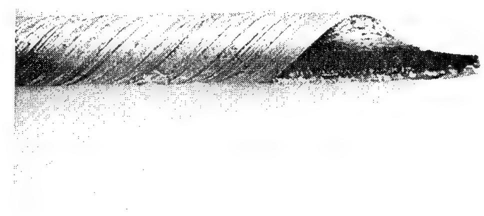

Fig. 21

Kinds of damage. It is, however, possible for single wires of the armoring to break as a result of excessive mechanical stress. For this reason the armoring wires are preformed when being applied to the cable core in such a way that a single broken wire does not spring out of the binding of the other wires and hit the high voltage phase conductors. It is advisable that the wires spring up slightly in order to spot out the damaged zone from the ground.

If, however, the cable sheath is likewise damaged by external influences, the penetration of moisture into the cable core must also be reckoned with. This moisture could lead to an increase in line loss and interfere with pulse operation as an echo. Moisture also increases the weight of the cable. These two effects are, however, of minor importance as compared to the changes which affect the physical properties as a result of continual changes in temperature between day and night and over the seasons.

Advantages of Alumoweld-armoring. By considering all the pros and cons of the armoring wires available, we arrive at the latest constructions for aerial cables, in which some of the wires consist of aldrey and some of alumoweld. Alumoweld wires have the following features:

- The same elctrolytic potential level as aldrey wires
- The coating of the alumoweld wires adheres better than that of galvanized

steel wires

- o Alumoweld wires are less sensitive to vibrations than galvanized steel wires
- o More resistant to the stresses caused by preforming of armoring and the laying process
- o Ensures reliable protection against corrosion in its steel core

By the use of these elements it is nowadays possible to meet the wishes of the power-line operators for attaining and even exceeding the maximum spans of phase ropes with the use of aerial cables.

Conclusions

It is concluded from the above that the mechanical problems of Self Supporting Aerial Cables, running along the same poles of overhead high-voltage lines, are solved using Aldrey and Alumoweld for armoring.

So the ASCR opens the way for modern communication networks with protective functions and bandwidth in reserve to meet increasing traffic demands. With ASCR the ESU's problems of long-distance-transmission can also be solved.

Acknowledgements

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TRI-LEAD CABLE AUTOMATIC PROCESS EQUIPMENT

by

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ABSTRACT

The development of the advanced system 370 IBM computer line required generation of new methods of manufacture for the tri-lead cable utilized in this equipment. In addition to development of new manufacture process, development of automated equipment was also required to meet theprojected high volume demands over a sustained period of time.

The problem was compounded by an infinite variation in cable lengths, impedance requirements, and types of terminals to be used. Material handling and transportation between process center and using plant locations also had to be addressed.

During the development of the equipment, major efforts were also directed into such areas as human factors, equipment safety, maintainability, design commonality process flow, equipment performance diagnostics, product quality assurance and process compatibility through the various process centers.

SUMMARY

The development of the advanced IBM System/370 computer line required generation of new methods of manufacture for the tri-lead cables utilized in this equipment. In addition to development of new manufacturing processes, development of high-speed, automatic equipment was also required to meet project high-volume demands over a sustained period of time.

This paper will present the techniques and equipment developed for handling and processing large volumes of tri-lead cable assemblies.

INTRODUCTION

The problem of developing automatic equipment for manufacture of the required cable assemblies was compounded by an infinite variation in cable lengths, impedance requirements, and the types of terminals to be used.

Cable lengths of up to 230 inches presented severe handling problems in transportation between process centers, shipment to using plant and computer assembly operations as well as processing through the automatic equipment.

Economic studies were performed which resulted in elimination of certain low-usage, special application cable assemblies from consideration for automatic processing. These cables would continue to be produced on an interim semiautomatic production line already in existence.

PRODUCT DESCRIPTION

Based on the economic studies conducted, the lengths of cables selected for automatic processing were established at a minimum of 6 inches and maximum of 230 inches. In addition, the combinations of cable types selected are listed as follows:

1) 90Ω, tuning-fork-to-tuning-fork (TF-TF) termination (Figure 1)

2) 50Ω, tuning-fork-to-tuning-fork (TF-TF) termination

3) 50Ω, tuning-fork-to-serpentine (TF-Serp) termination (Figure 2)

The actual tri-lead cable consists of three wires, with the two outer conductors considered as ground wires and the center conductor as the signal wire. An outer insulation holds all three cable wires side-by-side, in a flat cable configuration (Figure 3). Additional insulation, on the ground wires, provides electrical and mechanical separation between the signal and ground wires within one cable.

Either two tuning fork, or two serpentine; connectors (Figure 4) are attached to the wires on each end of the cable. Both ground wires are placed within one terminal.

The upper one-third of each tuning fork connector pair is encapsulated to form a single unit. The encapsulent extends onto the outer layer of the cable insulation and mechanically strengthens the area surrounding the cable-to-connector junction. The exposed lower portion of the tuning fork connector is inserted into a keyed nylon housing. The housing provides a separate chamber for each tuning fork connector in the pair, and prevents shorting, damage, and improper connector-to-

contact pin mating. A mechanical diagram of the assembly is shown in Figure 5.

The serpentine connectors are mounted in a connector block during the computer assembly operation, and, therefore, do not require a protective housing. The two ground leads are simply torn from the outer insulation, which remains as a protective coating over the signal lead.

For ease of handling at the computer assembly operation, approximately 50% of the 90- Ω TF-TF cables are subsequently processed into six-pac assemblies (Figure 6). This consists of placing a retaining clip over the housing T bars on six discrete cable assemblies.

PROCESS DESCRIPTION

The process steps required for cable manufacture, were formulated during the development of the cable itself. The process for the different types of cables are quite similar, so for the purpose of clarity, the balance of this paper will related to the 90- Ω TF-TF cable only.

The process steps for this cable, which are listed below, now had to be divided into major equipment groups or process centers. Possible modification for adaptation to the automatic equipment also had to be considered.

Process Steps

1) Measure length
2) Cut
3) Bundle and tie
4) Strip teflon jacket
5) Fold signal lead
6) Notch ground leads
7) Strip ML coating
8) Crimp connectors
9) Encapsulation
10) Lubricate connectors
11) Data stamp housing
12) Assemble housing
13) Test
14) Six-pack assembly.

These steps were divided into five major process centers. The first center covered the first three steps in the manufacturing process and was designated as Measure Cut and Package (MCP). In order to automatically process the cable in various lengths, through the equipment, an improved handling scheme had to be developed to replace the bundle and tie operation.

Consideration also had to be given to methods of shipment to using plants and ease of removal for computer assembly operations.

A disposable package concept (Figure 7) was developed, wherein the bulk cable material was packaged between layers of 0.014 inch thick cohesive coated blister board and 25# 0.004 inch thick steri paper material with both cable ends exposed for subsequent process operations. The package is of a standard width and variable length to accommodate the various cable sizes. An accordion fold concept was utilized, within the package, to avoid kinking or tangling of the cable as it was removed from the package.

The second equipment group covered process steps four through eight, with both ends of the cable being processed simultaneously (except for crimping). A straightening and trimming operation was added, prior to insulation strip, to ensure uniform lead location and length.

Due to the critical requirement of avoiding wire, or wire coating, damage during the strip operation, this process was divided into two separate steps: score and strip.

The sequence of events for this process center designated as Preparation and Termination (P&T) is shown in Figure 8.

The third equipment group provides the function required to perform the encapsulation operation. The encapsulation is formed by laminating together two pieces of the Kapton/Teflon material, one on each side of the terminated cable end, with both ends being processed simultaneously. The terminals are held in proper position by an Encapsulation Carrier (Figure 9) which also provides for retainment of the pieces of Encapsulation material. After encapsulation, the excess material is trimmed away to form the final configuration. The steps described are shown in Figure 10.

The fourth equipment group, designated as House and Test, performs process steps ten thru thirteen. An alignment operation, with sensors to detect the presence of all terminals, was added (prior to the functional operations) to avoid excessive scrap or material waste. Economics dictated inversion of the housing date stamp and assembly operations. The sequences of the process center are shown in Figure 11. All steps are performed simultaneously on both ends of the cable.

The last equipment group performs the six-pac operation by automatically assembling a retainer clip over the T bars on both ends of six previously completed discrete

cable assemblies. The retainer clip is flexed to allow entry of the T bars through the back and then straightened and pushed down to lock in place. This sequence is shown in Figure 12.

DESIGN CONSIDERATIONS

Product and Material Handling

The development of the cable packing concept provided a method of retaining the bulk wire during handling and processing operations. Creation of package handling and transport methods, therefore, became the next major task.

A magazine and cart concept (Figure 13) was developed that provided storage and transportation for up to 5,000 cable assemblies. Auxiliary equipment, which utilized a vacuum pickup system, was then designed to automatically load and unload the cable packages into and out of the process equipment.

The loading and handling of the encapsulation carrier also had to be improved over previous methods in order to meet the high-speed process requirements. Additional auxiliary equipment was developed to automatically load the terminals into the carriers and remove the cable packages from the P&T machine. The carriers are deposited on a simple belt conveyor and transported to the input station on the encapsulation machine. A magazine concept (Figure 14) was also used for loading the carrier into the carrier loader unit. The carrier load unit and conveyor are shown in Figure 15.

After encapsulation, a carrier unloader unit automatically opens the carrier and ejects the terminal from the locating block, to allow the unloader to place the completed cable into the package magazine. The carriers are then closed and fed on to a carrier magazine reload unit. The refilled magazines are then handcarried to the input station on the carrier load unit. The carrier unloader, package magazine load unit, and carrier magazine load unit are shown in Figure 16.

Upon completion of a final visual inspection operation, the housed and tested cable packages are placed in specially designed cardboard boxes for transportation to the using plants. These boxes have a tearaway end that permits easy access to the cable packages.

Material handling is simplified, throughout the line, by procurement of the bulk cable, packaging materials, terminals and encapsulation material in roll form. These material rolls provide ease in handling and storage, and can be rapidly loaded into the automatic process equipment.

Only the housings are received in loose form, and these are boxed in quantities convenient for handling on the equipment.

Process Compatibility

Understandably, each process center had to meet certain product parameters and requirements, but for each piece of automatic equipment, the most difficult task was the handling of the cable package and exposed cable ends.

To resolve these two critical items, and achieve compatibility between the process centers, a series of process parameters (Figures 17 and 18) were established to provide the limitations to be considered during the design phase. They were also used to determine where, within the total equipment line, the adverse effects on throughput and yield were being created. Although the process parameters had no permanent relationship to the completed cables, as all identity is lost when the cable is removed from the package, these specifications proved to be most important and valuable in development of the automatic equipment.

Equipment Accuracy

During the initial planning phases of the equipment program, both in-line and rotary types of equipment were considered for each process center. Factors such as the operations to be performed, special devices required, the critical nature of the operation and process parameter were considered.

Due to the nature of the cable package and flexibility of the cable leads, the questions of equipment accuracy became very difficult to answer. Accuracy of the working station had to be sufficient to meet product requirements, but what was needed, in the way of station-to-station index accuracy, seemed rather academic in light of lead flexibility.

It was felt that lead gathering and alignment would be required in most stations, and, therefore, index accuracy probably would not be that important. This approach, however, meant dealing with two variables at the same time. Also, when viewed from the standpoint of repeatability, it was deemed more advisable to obtain as much index accuracy as possible, provided the cost was not excessive.

Based on the various considerations discussed, a rotary index type of machine was selected for the P&T and H&T equipment. The encapsulation process was set up on an in-line concept. Shot pins on each critical station and guide bushing in the carriers provided the accuracy required for these operations. The MCP and six-pac processes were not particularly suited to either rotary or in-line concepts and were, therefore, designed as unique types of equipment.

Equipment Maintainability

Periodic reviews for maintainability were conducted by Maintenance Engineering throughout the design phase of

the program. Component selections were also reviewed based on their experience with similar applications on other equipment.

It was expected that the various types and quantities of equipment planned for cable manufacture would require a substantial maintenance effort during peak production periods. It was, therefore, imperative that the equipment be designed in a manner that would minimize downtime for repairs or preventive maintenance.

To achieve this goal, the equipment was designed, dimensioned, and toleranced for complete interchangeability of detail parts. This allowed for procurement of spares for all items subject to wear, damage or failure. In addition, the individual stations were designed as self-contained modules to permit rapid removal from the equipment if necessary. This was accomplished through the use of quick disconnects on a majority of the electrical and pneumatic lines. Maintenance boxes and manual mode control switches were provided for station operation in either an on-line or off-line condition.

Safety

Design considerations for safety were divided into two categories. First consideration was given to equipment operator safety. To protect the operator, all access doors and covers were interlocked, to remove electrical power and/or pneumatic pressure (via dump valves) whenever an interlock was broken. In addition, certain mechanisms were equipped with electromechanical or pneumatic brake units to halt potentially dangerous motion. Emergency power off buttons were located at strategic points around the equipment, and maintenance access doors were labeled with warning signs for access by trained personnel only.

Secondly, safety features were placed within the machine and access doors to protect the maintenance personnel. These consisted of safety shield over all high-voltage points, latches to hold doors and gates in an open position, and additional emergency power off switches and warning signs.

Periodic reviews were conducted by the safety department, during both the design and build phases of the program, to insure adequate protection for all personnel working on this equipment.

DESIGN GOALS

Equipment Performance Standards

In order to determine the number of machines required for each process center and subsequently monitor the performance on the production line, performance goals were established prior to commencement of the final design effort. The ultimate goals established (Table 1) were scaled on a monthly basis to reflect the learning curves and debug problems that could be expected in the early stages of equipment installation.

These goals were then used as a basis for evaluating program status and preparing projections on product unit cost and overall product capacity.

Table 1

EQUIPMENT PERFORMANCE STANDARDS

	MCP	P&T	Encap	H&T	6 Pac
Base Run Rate	1030	1090	1090	1025	360
Availability	85	80	85	90	90
Machine Efficiency	96	90	95	94	90
Machine Allowance	95	90	95	94	90
Operator Efficiency	85	85	85	85	85
Machine Yield	99	96	98	95	99
Adjusted Rate	671	576	697	658	222
Rate per Run Hour	791	720	818	730	244

Design Commonality

The initial concept phases of the program took into consideration the feasibility of utilizing common designs between the different process centers. The load/unload units required for each center offered the greatest possibility for this approach. A uniform distance of approximately 45 inches from the floor to the center line of the cable package was established as a criteria for all machines. A detailed concept was designed to perform the load/unload functions, and the ability to interface and perform the required tasks was reviewed for each center. The units were then customized to adapt to the electrical I/O channels and mechanical mounting arrangements unique to each machine.

The similarity in control function required for the P&T and H&T machines offered another opportunity for a common design effort. Solid-state (SLT) logic was selected for the control functions for both machines. Standard IBM 2701 control units were obtained minus the backpanels and circuit cards. A common control box was designed to mount on top of this unit (Figure 19). The matrix of indicators and control buttons are completely common for the two machines. The unique effort required to complete each control unit consisted of design of logic and interconnection and I/O circuits, plus personalized color selection and nomenclature on the control switches and indicator lights.

Equipment Protection

Automatic equipment of the type designed is highly susceptible to catastrophic failures, if the sequence of events is interrupted or changed due to mechanical binds, loss of control signals, or product jams. Collisions between operating mechanisms not only result in lengthy and costly repairs, but are also an additional hazard to production and maintenance personnel.

To prevent this condition from occurring, numerous sensors (in the form of reed switches, fiber optics, and microswitches) were utilized to determine the exact status of moving mechanisms and inhibit any out-of-sequence action.

A sensor on the P&T machine detects the presence of all wire leads, prior to the crimping operation, to prevent crimp tool breakage due to residual terminal that would be left in the crimp dies. It also prevents unnecessary terminal waste. Additional sensors are used to detect out-of-material conditions on the various machines. On the encapsulator machine, sensors are used to inhibit station function if a carrier is not present at the supply or lamination station.

Equipment Performance Diagnostics

The many sensors utilized in the equipment provided an opportunity to assist production and maintenance personnel by providing visual diagnostics on the condition of the equipment, as it operated or as to its status during an interrupt mode. The control panels on the H&T machine (Figure 20) and the P&T machine, contain indicators which are connected to all equipment sensors and provide a rapid status of what is happening.

A similar panel on the MCP machine (Figure 21) provides the same advantage on this equipment.

PROCESS EQUIPMENT DESCRIPTION

Measure Cut and Package Machine

The MCP equipment (Figure 22) is a dual-line machine, with a bulk wire supply on one end and a bulk card and paper supply on the opposite end. The card and paper are fed under a pair of pierce-and-cut-off dies utilizing vacuum transport paddles. The feed may be varied depending on package length desired. Vacuum transport platens pick up the card and paper stock, and position the card stock on the winding platform. The winding platform is then shifted to the wrap position. The bulk wire passes through a tensioning device and winding arm to a lead handler that grips the wire. As the wind arm makes its initial sweep, the lead handler rotates 180°, positioning the leading end of the wire in the proper location. Programmable winding pins are then raised, through holes previously pierced in the card, to interfere with subsequent sweeps of the wind arm. The spacing between the left and right pin banks, which is adjustable, and the number of pins used, determined the length of the cable. Upon completion of the wrap cycle, the sealing paper is pressed over the wire and the lead handler clamp is opened. The lead handler then rotates 180°, reclamps, and cuts off the wire. The sealing platen picks up the completed package (via vacuum) and transports it to a conveyor for unloading into a magazine.

A completed cable, ready for package sealing, is shown in Figure 23. The lead handler located on the left, will unclamp, rotate, grip and cut off the wire after sealing has been completed.

The transport functions of the equipment are accomplished through pneumatics, controlled by 110 VAC relays located in the rear control cabinet. Motor drives are used on the off-load conveyor, wrap arms, and feed paddles. The wrap pins are actuated by cams driven by a stepping motor. Control and wrap sequence is maintained by a logic section in the front control cabinet and encoders on the end of the cam shafts. The various wrap programs are entered through a rotary select switch located on the side of the cabinet.

Preparation and Termination Machine

The P&T equipment (Figure 24) is a twenty-four-position rotary index machine containing nineteen active stations. This machine prepares and positions the conductors, and terminates each end of the cable with two connectors utilizing a crimping process. The connectors are then automatically loaded into the encapsulation carrier by a carrier loader, which positions the contacts in the proper relationship for the encapsulation operation. A conveyor belt then transports the carriers to the encapsulation machine.

The rotary index machine is approximately 4 feet high and 7 feet in diameter. The circular indexing table, which contains 24 package-holding fixtures, is driven by a 1 1/2 hp, 1725 r/min motor. Cams attached to the index cam shaft, which rotates at 15 r/min, activate switches that provide timing signals to the IBM 2701 logic control unit.

After a package is loaded into the fixture, by the load unit, clamping action is activated (during indexing) by a pair of stationary cams acting on the fixture cam follower. This releases the fixture clamp springs to clamp the package. The fixture is opened by the same cam working in reverse direction at the unload position. In addition, at the first insulation strip station, a guide holds the cam follower to insure that the fixture will not open in spite of the stripping force required.

A plan view layout (Figure 25) of the P&T machine and the accompanying chart (Table 2) reflect the sequence of events as the cable package progresses through the equipment.

Encapsulation Machine

The encapsulation equipment (Figure 26) is a 7-station, in-line machine which utilizes an incremental chain drive to transport the carriers through the machine. This machine laminates a kapton/teflon material between the terminal and cable insulation to form a strain relief for the cable conductors.

Table 2

P&T MACHINE — OPERATIONAL SEQUENCE

Station Number	Name	Description/Function
1	Load	Supplies packages to machine
2	Align	Straighten leads
3	Trim	Cuts leads to 1.00 inch length
4	Score	Heat score insulation for stripping
5	Strip	Remove insulation
6	Signal Fold	Separate signal from grounds
7	Ground Cut	Shorten ground leads
8	Insulation Heat	Prepare ground insulation for removal
9	Insulation Strip	Remove ground insulation
10	Ground Lead Form	Gather leads for crimping
11	Signal Form	Position signal for crimping
12	Test	Perform continuity check
13	Crimp #1	Attach first ground connector
14	Idle	Spacing
15	Crimp #2	Attach second ground connector
16	Idle	Spacing
17	Crimp #3	Attach first signal connector
18	Idle	Spacing
19	Crimp #4	Attach second signal connector
20	Idle	Spacing
21	Degrease	Remove crimp lubrication
22	Idle	Spacing
23	Unload	Remove package from machine
24	Reject	Remove reject product

The encapsulation carriers move through the machine in a channel, driven along by projections on the feed chain. The chain is indexed by a pneumatically-operated, 360° rotary drive index unit. A slip clutch prevents damage should a jam occur.

The actual encapsulation functions are performed through the stations in the following order.

1) Load Station — Releases and feeds carrier at the proper center distance into the feed chain for transport through the machine.

2) Supply Station — Cuts off and inserts four pieces of kapton/teflon material into the encapsulator carrier.

3) Pre-heat Station — Pre-heating of the material prevents bubbling of the encapsulant and achieves a homogeneous bonding of the teflon during lamination.

4) Laminate Station — Heated platens are inserted through the carrier to laminate the material around the terminals and exposed wire leads.

5) Cooling Station — The cooling hardens the encapsulant material so that an accurate trim can be accomplished.

6) Trim Station — Trim punches are inserted through the carrier to remove excess material and cut the encapsulation to its final form.

7) Trim Eject Station — Residual encapsulation trimmings are pushed out of the carrier and dropped into a removable container.

House & Test Machine

The House & Test equipment (Figure 27) is a 10-position rotary index machine with eight active stations. This machine lubricates and houses the connectors, and performs the required tests on the completed cable assemblies.

The rotary index machine is approximately 4 feet high and 6 feet in diameter, mounted on a 7 foot square base. The circular indexing table, which contains ten package holding fixtures, is driven by a 3/4 hp, 1725 r/min motor. Cams attached to the index cam shaft activate switches that provide timing signals to the IBM 2701 logic control unit.

A cable package is removed from the package magazine and loaded into the fixture by the load unit. The fixture is closed to a pre-clamp position, while aligners on the front of the fixture bring the leads into approximate horizontal and vertical location. Funneled aligners on the next station perform the final horizontal and vertical

alignment, and push the encapsulated area back into a banking surface that matches the encapsulate configuration. Final clamping action is then accomplished by a pneumatic cylinder striking the clamp rod that protrudes from the back of the fixture.

After lubrication is applied to the ends of the connectors, at station 3, the package is indexed to the housing station. The housings are oriented and fed into the station by a dual-track, vibratory feeding system. A collapsible funnel mechanism, containing the two housings, picks up the ends of the connectors and starts the insertion into the housings. The funnel then collapses and swings out of the way while a pusher continues to insert the housing on to the final latch point. Internal springs reset the funnels on the station retraction stroke.

The machine number and manufacturing date code is then hot stamped on one housing at station 6, and the package is indexed to station 8 for test. Split test probes are inserted into the connectors, through openings in the end of the housing, and the cables tested for opens, shorts, insulation resistance, and signal-to-ground ratio. These are static tests where a DC voltage is applied to a cable assembly and its effect measured after a fixed time interval.

The split test probes provide a four-point measuring technique to accurately measure the voltage drop across a low resistance (less than 0.01Ω).

By using a four point system (Figure 28), voltage errors due to contact resistance are minimized.

After completion of the test cycle, the package is indexed to station 9. A pneumatic cylinder located at this station opens the package fixture and resets the fixture clamp rod. If the cable had failed the electrical test, a reject mechanism is activated and the package removed from the fixture and deposited in a removal container. Acceptable cables are indexed to station 10, where an unload unit removes the package and deposits it in a package magazine.

A plan view layout of the H&T complex is shown in Figure 29.

Six-Pac Machine

The six-pac machine (Figure 30) is manually loaded with six cable packages in a buffer/transfer station. The safety door is closed and the transfer cycle start button depressed.

The cards are moved sideways by the transfer rail or pusher onto the assembly platform where they are nested between the pusher rail and the stationary rail. The assembly station locating/discharge pins are driven down from above, through the package locating holes to maintain proper card alignment.

The extend fingers are driven up on each side of the two rows of leads (cables). The housing holddown feet are moved into position, and a slight pressure is placed on each stack of housings. The fingers then gather the housings and pull them away from the cards until they extend an additional 1/2 inch from the card, or a total dimension of 1-3/4 inches from the card end to the housing end. The extend cycle also drives the housings away from the holddown feet and under the spring-loaded housing holders. The assembly bed plate is raised to bring the housings into alignment with the retainer clip. The retainer clips are fed into the machine from preloaded magazines located at the top of the assembly station.

The assembly station locating pins are retracted from the cards. The retainer is bowed and the housings are pushed into the retainer until fully seated. The locating/discharge pins are moved back towards the elevators 5/16 inches so that they again center on the card locating holes (in pushing the housings into the retainers, the cards are also moved and the pins are retracted to avoid cable damage). These pins are then driven through the card holes, the assembly bed plate is lowered to its bottom position, and the completed six-pac assembly is deposited in the storage elevator by the location/discharge pins. The elevators are offset, sideways, with each assembly, to prevent the housings and retainers from stacking on top of each other and causing an uneven stack.

CONCLUSIONS

The use of automatic equipment can provide savings in space and manpower requirements over manual methods. Economic justification, however, usually provides the major emphasis when considering projects of this type. The economics, in terms of unit hours per cable realized as the result of this program are shown in Figure 31.

The economic savings achieved, as depicted by this chart, can only be realized through careful planning and establishment of the criteria to be followed and goals to be met during various stages of equipment development.

Biography

Mr. D.E. Short joined the IBM Corporation in July 1953 as a tool/modelmaker apprentice. After graduation from this program in 1956, he spent the next 2 years as a tool and modelmaker at IBM's Endicott and Owego plants.

In 1959, he was transferred to Manufacturing Engineering where he spent the next 10 years designing and developing tools and methods of manufacture for numerous aerospace programs. Activity included such programs as Titan, OAO, Gemini, Saturn V and the IBM System/4 Pi line of avionic computers. During this time, he specialized in methods of manufacture and assembly of solid state memory units.

In 1969 Mr. Short was responsible for managing the design of tools and equipment for fabrication and assembly of various aerospace products.

During 1970 Mr. Short was manager of MST Cable Equipment Design, responsible for electrical/mechanical design of the House and Test and Encapsulation machines. In addition, he was responsible for coordination of fabrication, setup, and debug of these units plus the "A" mag load/unload and carrier unload units.

Mr. Short is manager of MST Cable Process Engineering, responsible for support and modification of production equipment for manufacture of MST tri-lead cable assemblies, cable production unit hour costs, cable production yields, and cable equipment production capacities.

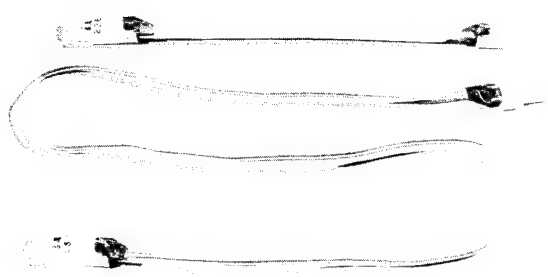


Figure 1. 90-Ω Termination

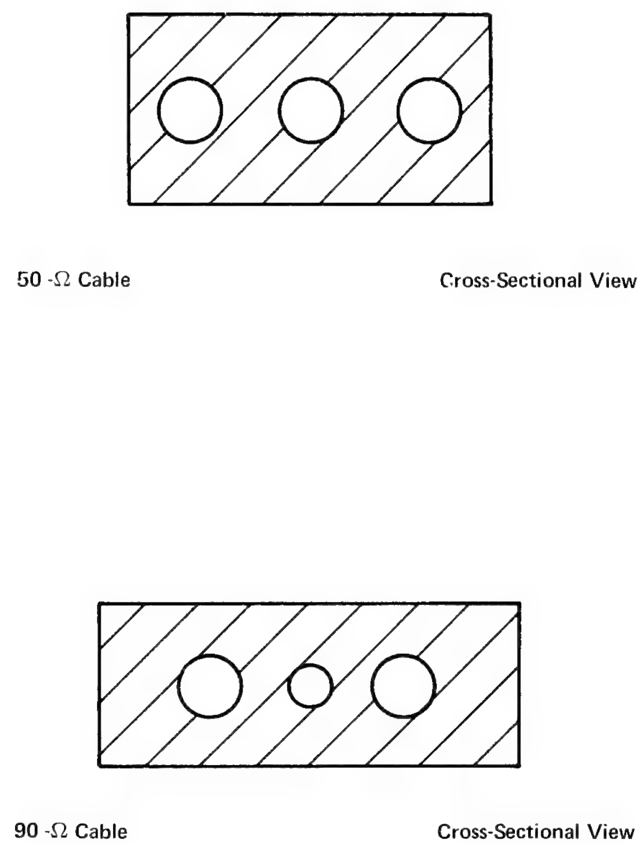


Figure 3. Cable Configuration

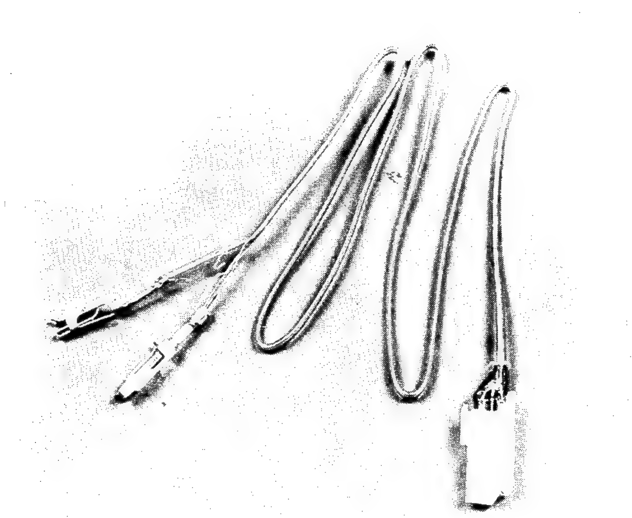
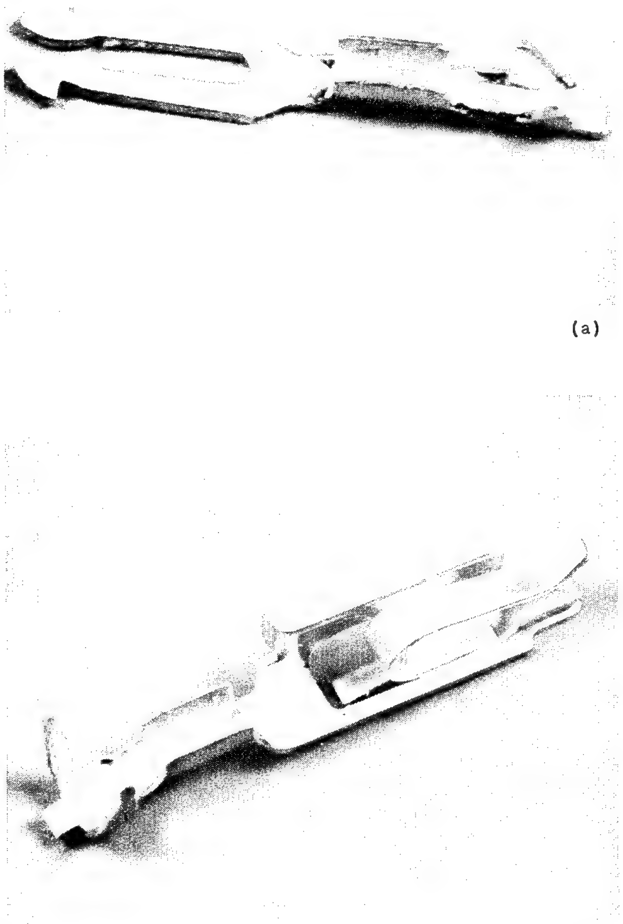


Figure 2. 50-Ω Termination



(a)

(b)

Figure 4. Cable Connectors

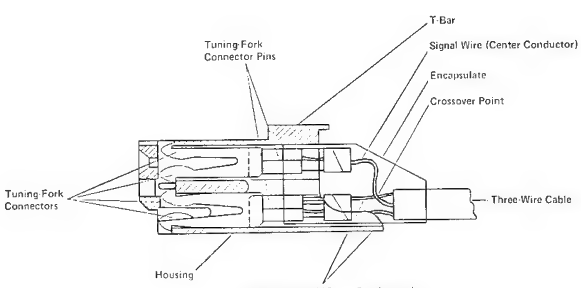


Figure 5. Tri-Lead MST Cable, Mechanical Diagram

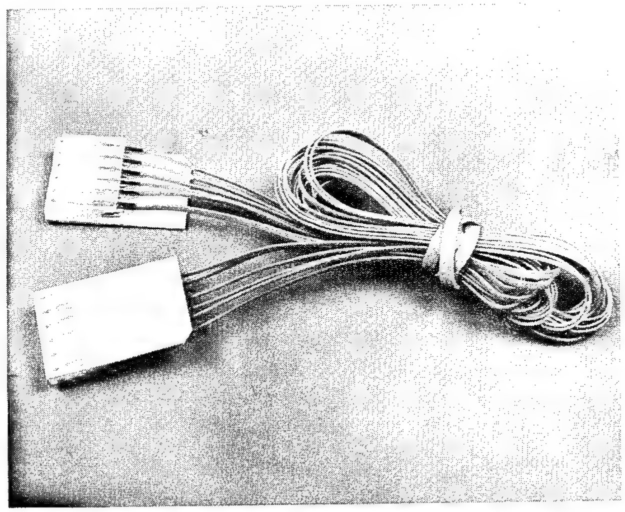


Figure 6. Six-Pac Assembly

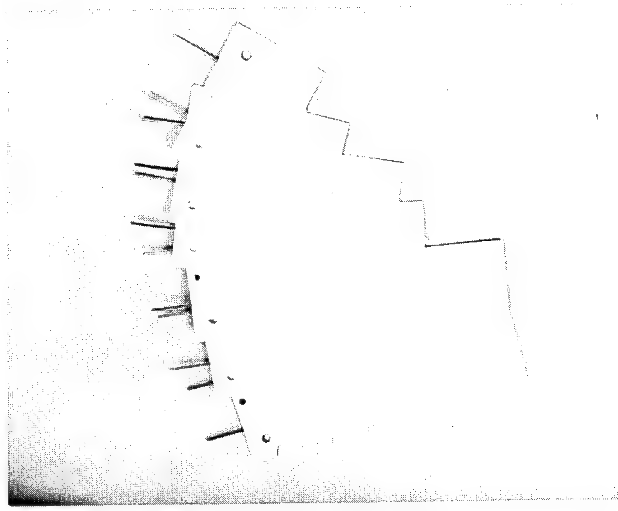
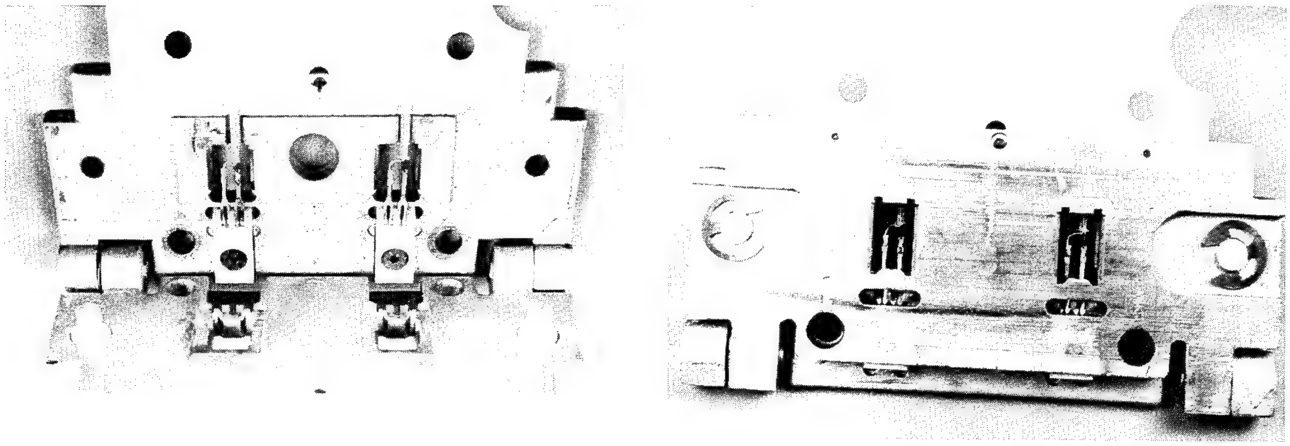


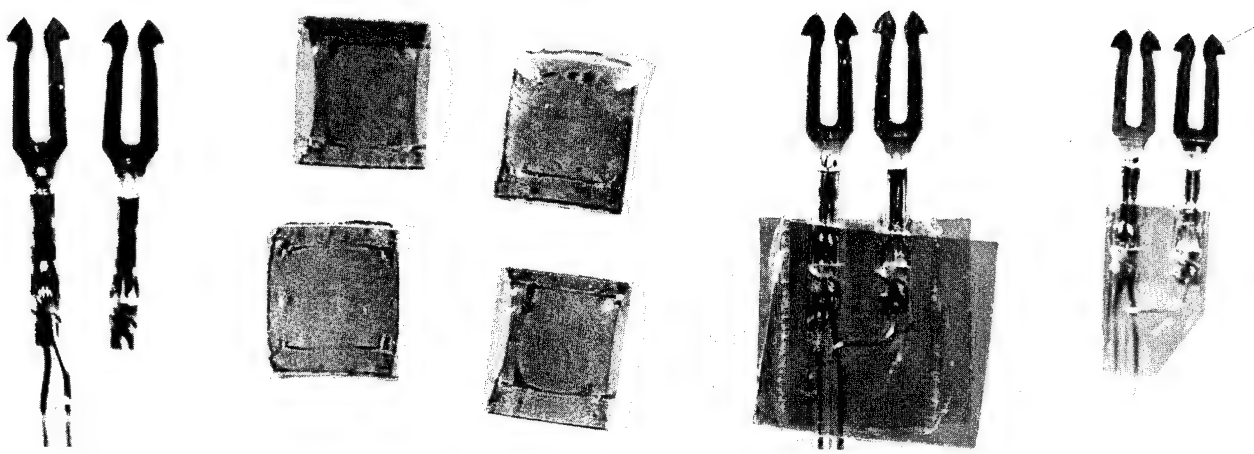
Figure 7. MCP Packages

Figure 8. P&T Process



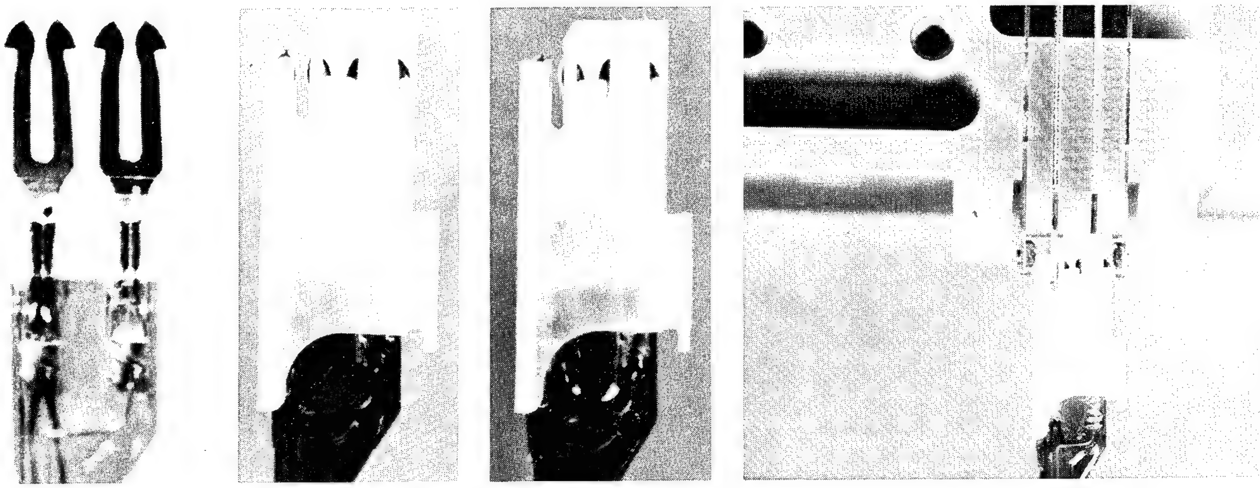
(a) (b)

Figure 9. Encapsulation Carrier



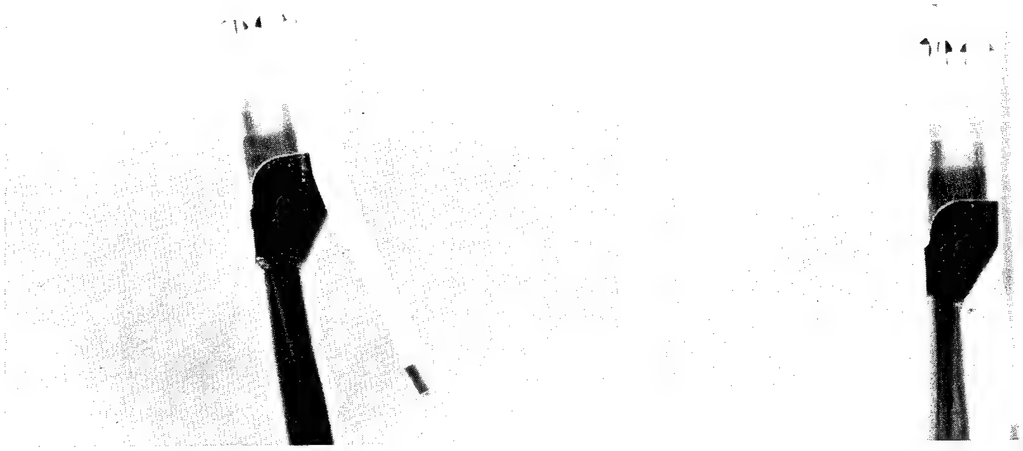
(a) (b) (c) (d)

Figure 10. Encapsulation Sequence



(a) (b) (c) (d)

Figure 12. Six-Pac Operation



(a) (b)

Figure 11. House and Test

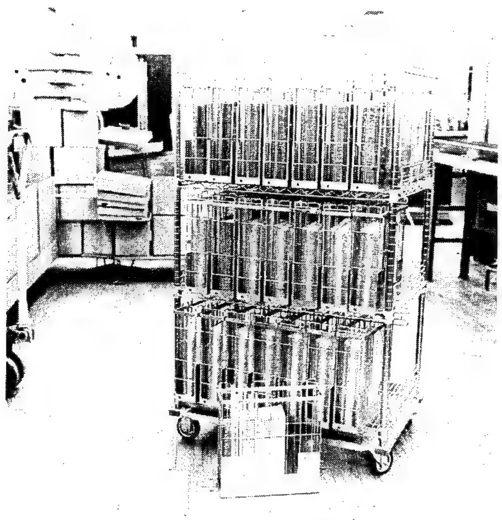


Figure 13. Magazine and Cart

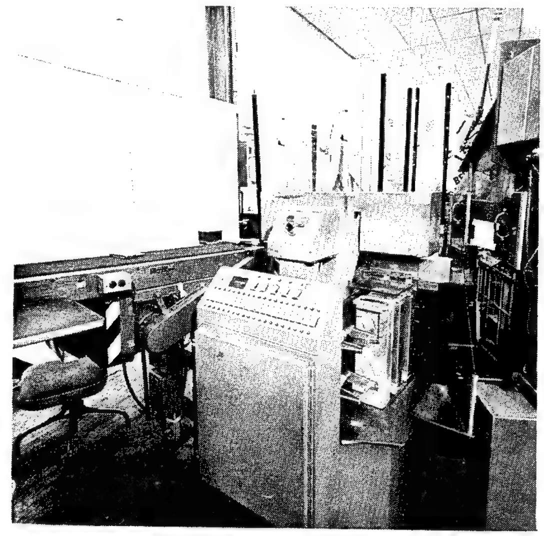


Figure 15. Carrier Load Unit and Conveyor

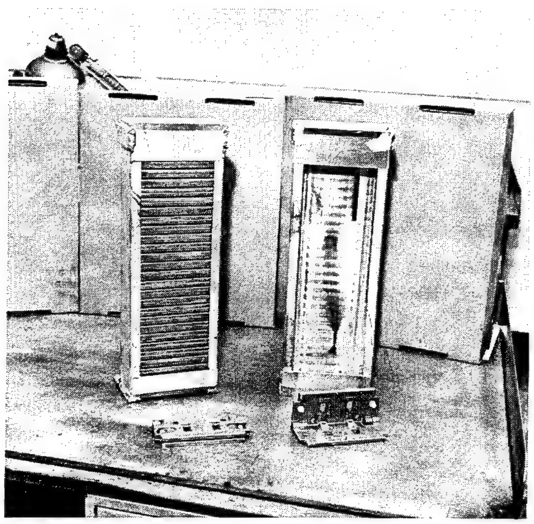


Figure 14. Magazines

Figure 16. Carrier Unloader, Package Magazine Load Unit, and Carrier Magazine Load Unit

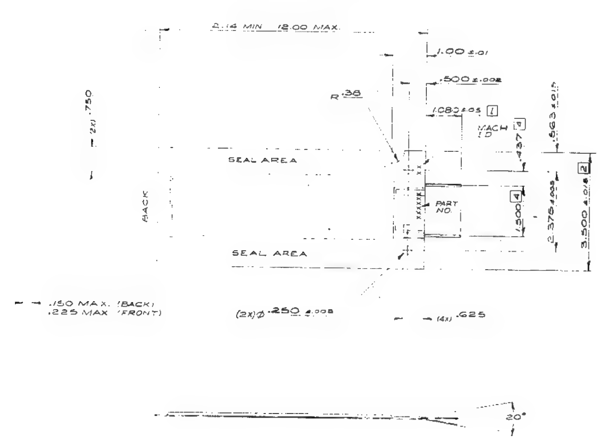


Figure 17. Process Parameters - MCP

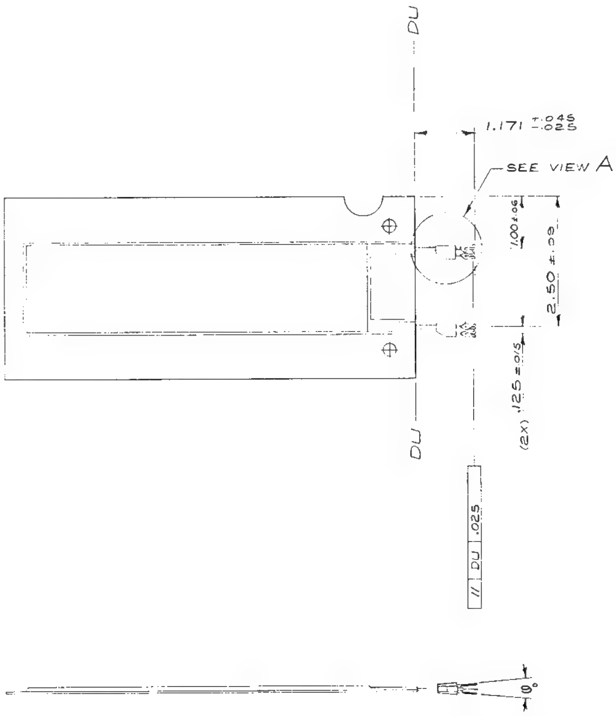


Figure 18. Process Parameters - Encapsulation

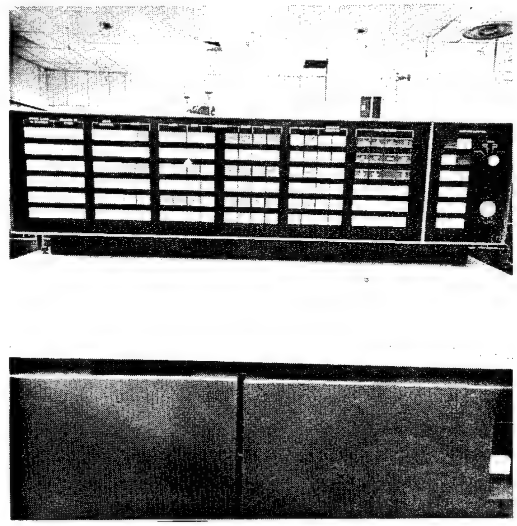


Figure 20. H&T Machine

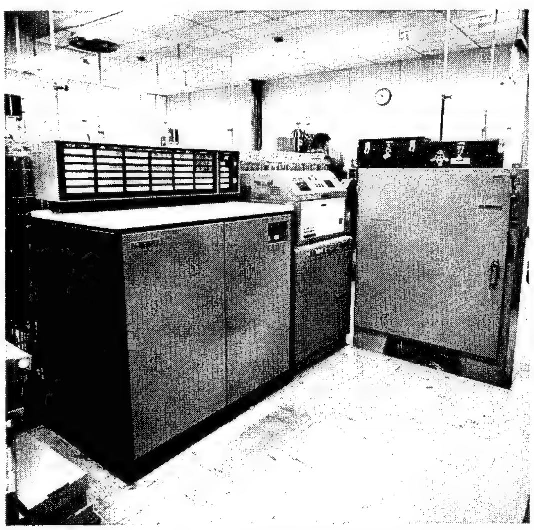


Figure 19. IBM 2701 Control Unit

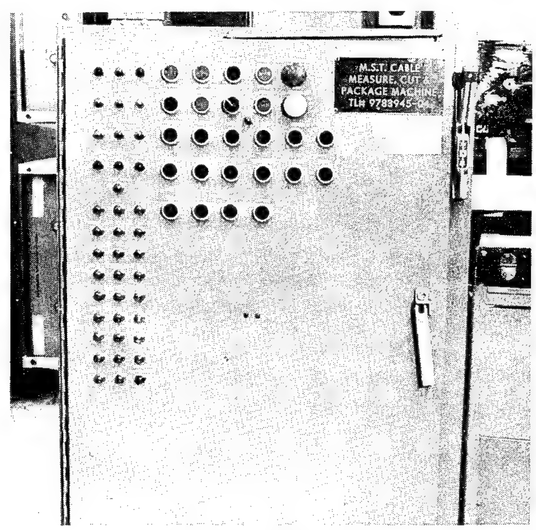


Figure 21. MCP Machine

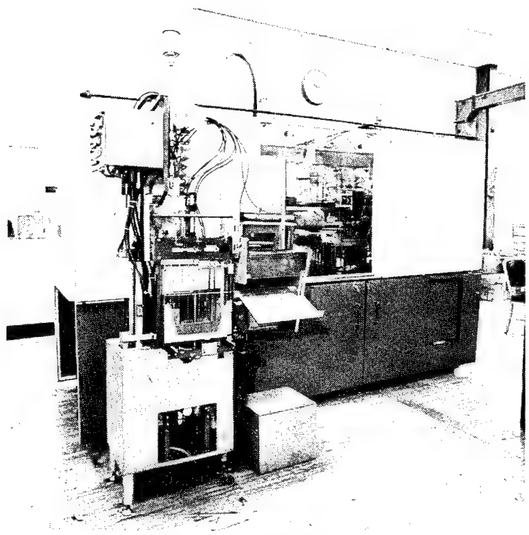


Figure 22. MCP Equipment

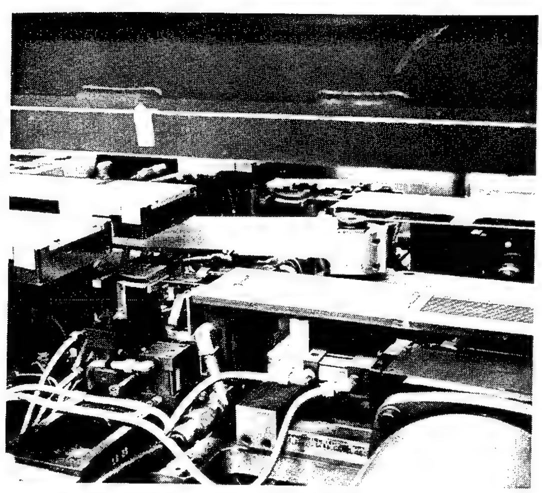


Figure 23. Completed Cable

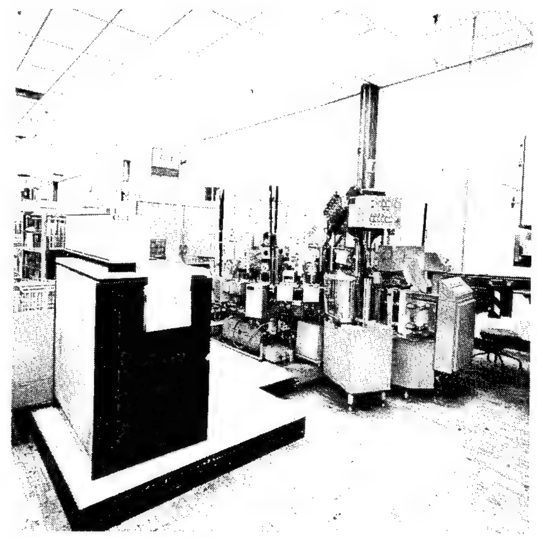


Figure 24. P&T Equipment

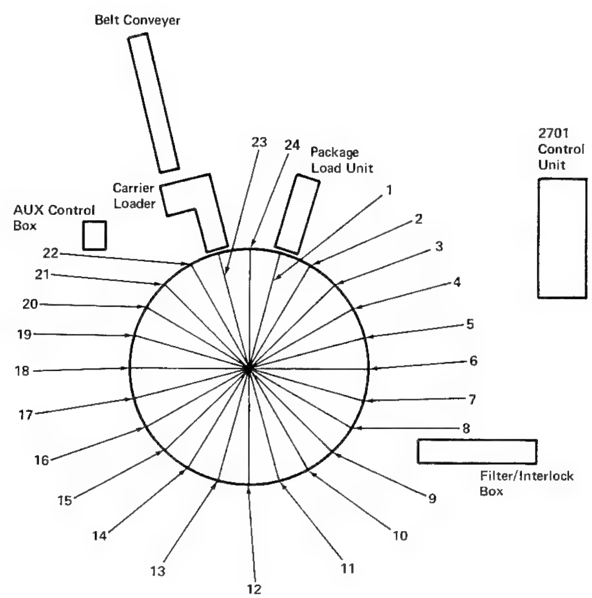


Figure 25. P&T Machine Physical Layout

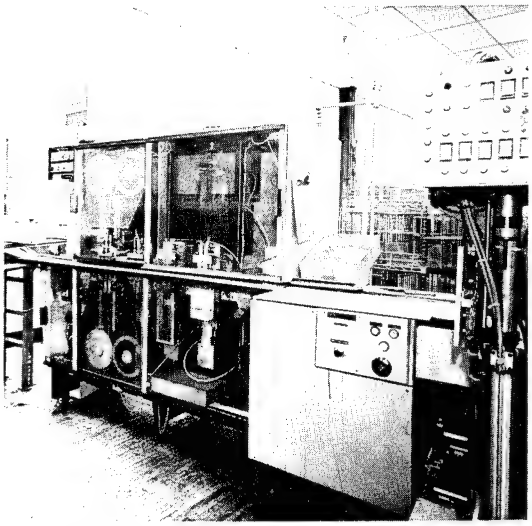


Figure 26. Encapsulation Equipment

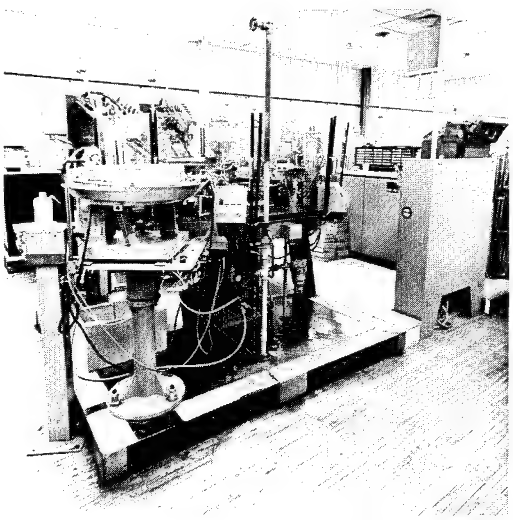
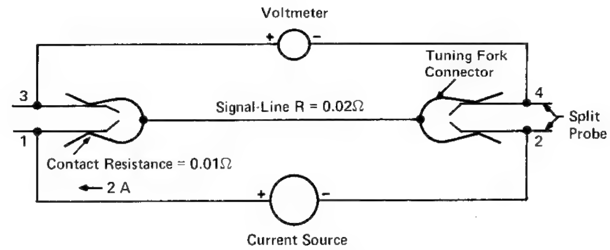


Figure 27. H&T Equipment



Physical Diagram 4-Point System

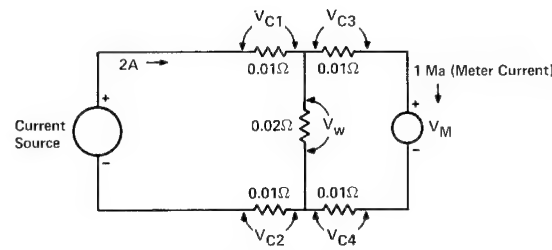


Figure 28. Schematic Diagram 4-Point System

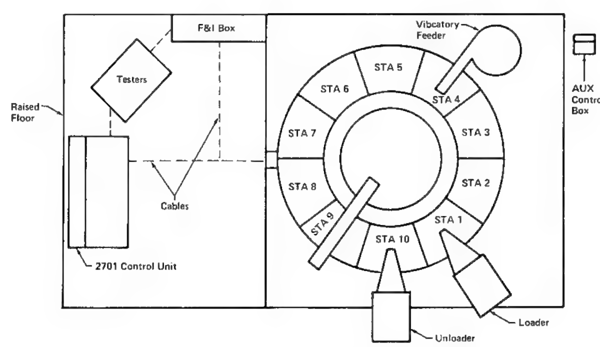


Figure 29. H&T Complex - Plan View

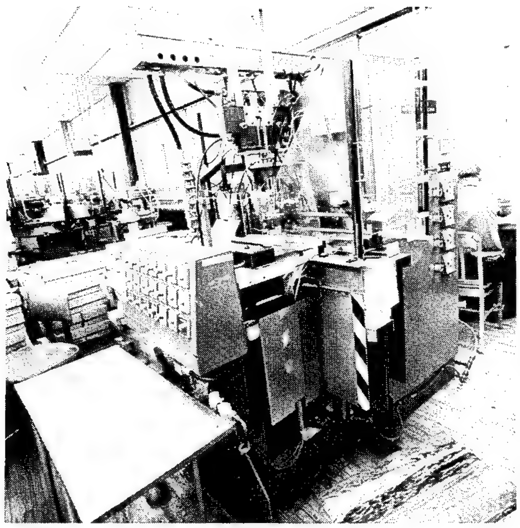


Figure 30. Six-pac Machine

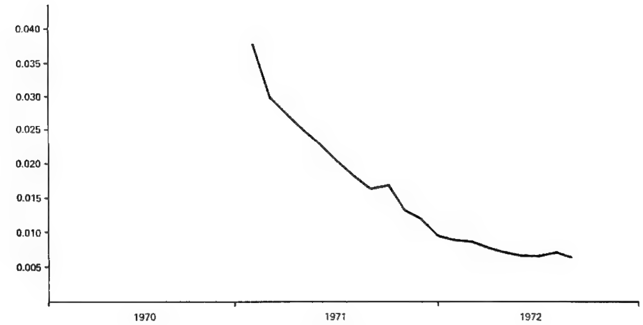


Figure 31. Unit Cost

FLAT CABLE CROSSTALK AT AUDIO AND VIDEO FREQUENCIES

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Norcross, Ga. 30071

ABSTRACT

To assist in the evaluation of flat cables for use in audio and video frequency systems, crosstalk measurements at 1 kHz and 1 MHz are presented for two Ansley Corporation flat cables (UNI-FIELD and AS-17). The effects of ground conductors and dielectric and metallic spacers between cables are given. The results are compared with theory and with switchboard cable measurements. Pair-to-pair and power sum crosstalk, and the capacitive and inductive components are discussed.

INTRODUCTION

The economic advantage of mass termination may make flat cables attractive for use in a number of audio and video frequency systems. To assist in their evaluation, we have measured crosstalk at 1 kHz and 1 MHz the two Ansley Corporation flat cables shown in Figure 1:

(1) Mylar-vinyl flat conductor flat cable, IPC-FC-220 designation AS-17. .062" conductors on .100" centers.

(2) UNI-FIELD[1] dual-dielectric flat cable. #28 AWG round conductors on .025" centers.

For comparison, similar measurements were performed on a conventional switchboard cable.

THEORY

Suppose a voltage V_s at frequency ω (rad/sec) on an active pair produced near and far end crosstalk voltages V_n and V_f on a neighboring quiet pair. The pairs interact over a length ℓ through the mutual inductance L_m and capacitance C_m (both per unit length). Both pairs are terminated in an impedance Z_L which is of the order of the line impedance Z_O. If the coupling is weak and ℓ is much less than a wavelength, then the crosstalk voltages obey[2]

$$\begin{aligned} V_n/V_s &= \tfrac{1}{2}\, j\omega\ell\ (C_m Z_L + L_m/Z_L) \\ V_f/V_s &= \tfrac{1}{2}\, j\omega\ell\ (C_m Z_L - L_m/Z_L) \end{aligned} \quad (1)$$

If we assume filamentary conductors and neglect the effects of the dielectric and of other conductors, then C_m and L_m can be expressed[3] in terms of a geometrical factor F:

$$\begin{aligned} C_m &= (C_1 C_2/4\pi\varepsilon)F \\ L_m &= (\mu/4\pi)F \end{aligned} \quad (2)$$

where C_1 and C_2 are the self-capacitance of the active and quiet pairs, ε is the effective dielectric constant, and μ is the magnetic permeability. For the intracable geometry (Figure 2),

$$F = \int_{-\infty}^{\infty}\left(\frac{1}{d_1} - \frac{1}{d_2}\right)dz_{P=R} - \int_{-\infty}^{\infty}\left(\frac{1}{d_1} - \frac{1}{d_2}\right)dz_{P=Q}$$

$$= 2\ell n\,\frac{d^2 - (a-b)^2}{d^2 - (a+b)^2} \quad (3)$$

Two special cases of (3) are

$$F = 2\ell n(4/3) = 0.57 \quad , a=b=d/4 \quad (4)$$

$$F \simeq 8ab/d^2 \quad , d \gg a,b \quad (5)$$

Because of the assumptions involved, this theory should be regarded as only a first-order approximation. Its purpose is to provide qualitative insight rather than accurate prediction. An illustration of this will be given later.

MEASUREMENTS

Untaped stacks of three identical cables were laid in a metal trough. The active and quiet pairs were excited in a balanced mode by means of transformers. Audio frequency crosstalk measurements were performed with a Lock-in Amplifier on 50' lengths of cable with 600 ohm terminations. 1 MHz crosstalk measurements were performed with a Wave Analyzer on 10' lengths of cable with 110 ohm terminations.

To determine the power sum, the crosstalk induced on a single pair in the middle of the three-cable stack by each of the other pairs was measured. The square root of the sum of the squares of these pair-to-pair crosstalk voltages was then calculated. This value in dB is the power sum.

The capacitive and inductive components of the crosstalk were determined by opening and shorting the end of the quiet pair opposite the detector.

RESULTS AND DISCUSSION

When no ground condutors are used, Equation (4) applies to both cables considered here. Estimating ε from the propagation velocity, (2) then gives for the AS-17:

$$C_m = 0.91 \text{ pf/ft.}$$

$$L_m = 17.4 \text{ nh/ft.}$$

Equation (1) can then be used to predict the crosstalk, and in Table I the agreement with the measured values is seen to be good. It is apparent that the capacitive component is dominant only at audio frequencies.

TABLE I
Intra-Cable NEXT (dB) for Adjacent Pairs of the Ansley AS-17 (No Ground Lines)

Component	Theory (Eq.1))	Measured
(A) Z_L = 600 ohms; $\omega/2\pi$ = 1 kHz; ℓ = 50'		
Capacitive	- 81	- 75
Inductive	-107	-108
Total NEXT	- 81	- 76
(B) Z_L = 110 ohms; $\omega/2\pi$ = 1 MHz; ℓ = 10'		
Capacitive	- 50	- 47
Inductive	- 46	- 48
Total NEXT	- 42	- 42

The effect of using ground conductors between the active and quiet pairs in the AS-17 cable is shown in Figure 3. The grounds provide no magnetic shielding, and hence the inductive component decreased in accordance with the geometrical factor F. The capacitive component decreases much faster than F, however, because of electrostatic shielding by the grounds. This is the reason for the failure of the filamentary-conductor theory to predict the correct capacitive components in Figure 3. With two or more ground present, Figure 3 shows the crosstalk to be predominantly inductive, with only a slow decrease reresulting from the insertion of additional grounds. Most of the crosstalk reduction is achieved by inserting the first ground.

The power sum crosstalk with and without spacers between the cables is summarized in Table II. With no spacers, inter-cable crosstalk dominated the AS-17 power sum. Hence its crosstalk would be much less if stacks of cables were unnecessary. By contrast, intra-cable crosstalk dominated the UNI-FIELD power sum. This may be because of the field confinement

TABLE II
BALANCED POWER SUM CROSSTALK FOR 50' CABLE LENGTH; ONE GROUND CONDUCTOR BETWEEN EACH PAIR

	Ansley AS-17	Ansley UNI-FIELD	Switch-board
(A) 600 Ohm Terminations Used; NEXT in dB at 1 kHz			
With No Spacer	- 73	- 96	-109
With Dimple Strip	- 93	- 97	
With Copper Foil	-107	- 97	
(B) 110 Ohm Terminations Used; NEXT in dB at 1MHz			
With No Spacer	- 16	- 35	- 57
With Dimple Strip	- 30	- 36	
With Copper Foil	- 48	- 35	

provided by the UNI-FIELD's outer dielectric.[4]

Measurements made with the same apparatus on a conventional 26 gauge 25-pair switchboard cable are given in Table II for comparison. The -109 dB and -57 dB values are several dB lower than the mean of a sampling of switchboard cable measurements from other workers. Regardless of whose numbers are used, however, the two flat cables without spacers have greater crosstalk than switchboard cable at both 1 kHz and 1 MHz. The UNI-FIELD is a definite improvement over the AS-17, but the use of additional ground conductors would be necessary for it to match the switchboard cable's crosstalk performance. The penalties in cost and space incurred by the use of additional grounds would then have to be weighed against the cost savings due to mass termination.

ACKNOWLEDGEMENTS

The author wishes to thank T. J. Kessler, J. W. Balde, and N. A. Strakhov for many helpful discussions, and A. J. Long for performing many of the measurements.

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W. B. Gandrud received a B.S. in Physics from the University of Alabama in 1961 and a Ph.D. in Physics from The Johns Hopkins University in 1968. He became a Member of the Technical Staff of Bell Telephone Laboratories, Whippany, New Jersey in 1968. He worked there on materials and devices for nonlinear optics, and on the electrical properties of backplane interconnections. He is currently working on optical fibers at Bell Telephone Laboratories in Norcross, Ga.

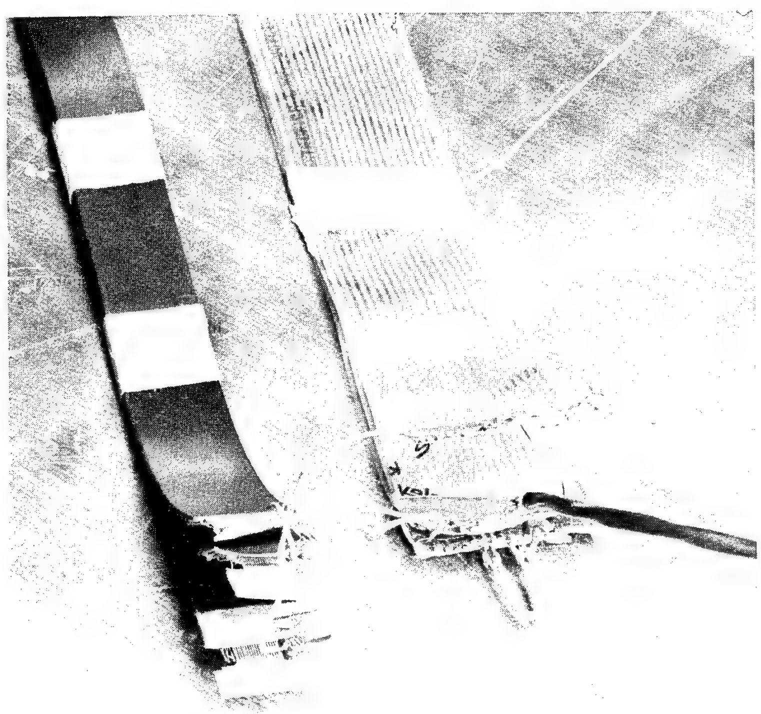
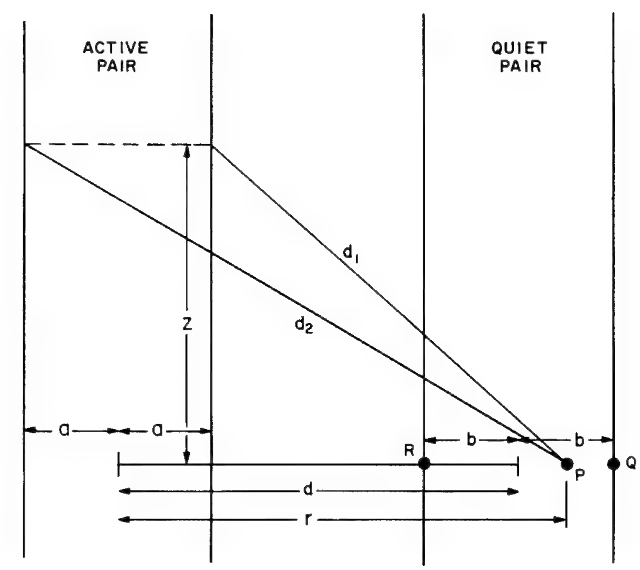


Fig. 1. Stacks of the two Ansley flat cables tested. The UNI-FIELD is on the left and the AS-17 on the right.



INTRA-CABLE CROSSTALK GEOMETRY

Fig. 2

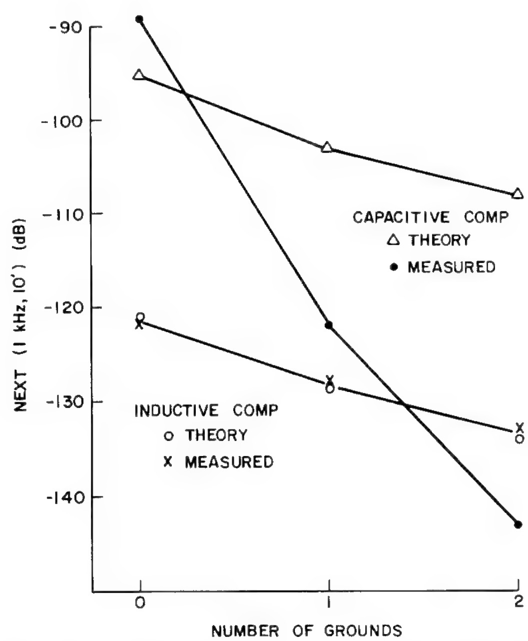


Fig. 3. The effect of grounds on the near-end intra-cable crosstalk in the Ansley AS-17 cable.

EXPLANATION FOR THE DUAL DIELECTRIC PHENOMENON IN DIFFERENTIAL CROSSTALK CONTROL

Joseph B. Marshall   Robert B. Linville

Ansley Electronics Corp.
Subsidiary of Thomas & Betts Corporation

Introduction

The UNI-FIELD "Black Magic T.M." flat cable as a new multisignal transmission line was presented at the Twentieth International Wire and Cable Symposium. The UNI-FIELD "Black Magic T.M." flat cable is a dual dielectric multiconductor flat cable, where the cable core and jacket are embodied in two distinctively different insulation materials: the conductors are embedded in a good, low dielectric constant insulator, while the jacket is a higher dielectric constant material. (Figure 1) The geometry of the cable is based on the right relationship between -

a. Center distance of signal to ground and signal to signal conductors

b. Cable core thickness

c. Jacket thickness

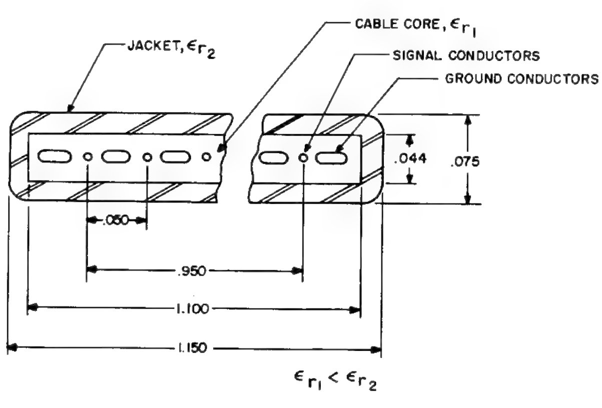


Figure 1 - Cross-section of prototype UNI-FIELD "Black Magic T.M.". cable.

The prototype UNI-FIELD "Black Magic T.M." cable was described with detailed explanation for all transmission line characteristics. Crosstalk control was the main specialty of the new cable. The UNI-FIELD "Black Magic T.M." flat cable was designed for and does one thing extremely well: reduces the generally most troublesome Differential crosstalk below the level of any other crosstalk component. The performance was proven clearly, amply and doubtless; however, a detailed explanation for this phenomenon was not available at that time.

Since then extensive research and further tests conducted by the authors led to a satisfactory answer worthwhile for this presentation.

The Differential Crosstalk

In today's communication and computing equipments more and more data is being transmitted in digital form. The transition times of the signals are approaching and exceeding 1 nanosecond. Using conventional flat cables and twisted pairs with such signals the interference would become so high that unintentional switching would occur. The crosstalk is particularly high at the load end of the circuit and in worst case it could be as high as 40% of the transmitted signal. The general term used for this interference is Far End crosstalk or Differential crosstalk.(1) (Figure 2) Differential crosstalk increases by the length of cable and also by the faster pulse rise time. It is spike shaped and has a polarity opposite to the transient on the Active line. The UNI-FIELD "Black Magic T.M." flat cable limits and controls this Differential crosstalk well below the acceptable level. Therefore, it presents an entirely new and economical multisignal cable for the fast rise time data transmission field. This is accomplished by the dual dielectric phenomenon that characterizes the

UNI-FIELD "Black Magic™" cable family.

Crosstalk in Homogeneous Dielectric Media

In order to review crosstalk coupling parameters a diagram is shown on Figure 3 depicting two adjacent uniform signal lines; one of them carries a pulse type signal. Each of them has its inductance, capacitance, resistance and conductance. There is inductive and capacitive coupling between the two lines. The crosstalk noise is due to mutual inductance and mutual capacitance.

A step introduced into the Active signal line will affect the adjacent Quiet line. The step is composed of both voltage and current in a ratio determined by the Z_O of the transmission lines. As the step proceeds down the Active signal line it is accompanied by its electrostatic and electromagnetic fields.

These fields induce a voltage into the adjacent Quiet line. This induced voltage (and associated current) will propagate in both the forward and backward direction at the same speed as the inducing step. However, there is a distinctive difference between the forward and backward crosstalk:

The capacitively coupled portion of the voltage will propagate in both directions with the polarity of the inducing voltage. The inductively coupled portion will propagate backwards with the same polarity as the inducing current, but it will propagate with an opposite polarity in the forward direction.

The effects of these interacting fields on the Quiet signal line are:

a. The Backward crosstalk will be the sum of both the capacitive and inductive effect. This is a miniature replica of the input pulse and it reaches the maximum amplitude when twice the propagation time of the Quiet line is equivalent or greater than the input pulse rise time. (e.g.- an air dielectric Quiet signal line will reach the maximum Backward crosstalk when six inches or longer, with a 1 nanosecond rise time pulse travelling in the Active signal line.)

b. Forward crosstalk will be the difference of the inductive and capacitive coupling effects because they are opposite to each other in polarity. Coupling coefficients may be expressed by the following formulas [2]:

$$K_L = \frac{L_{12}}{(L_{11} \quad L_{22})^{\frac{1}{2}}}$$

$$K_C = \frac{C_{12}}{(C_{11}\ C_{22})^{\frac{1}{2}} + \ C_{12}}$$

where

K_L	:	inductive coupling coefficient
L_{11} & L_{22}	:	line inductances of the two signal lines respectively
L_{12}	:	inductive coupling between the two adjacent signal lines
K_C	:	capacitive coupling coefficient
C_{11} & C_{22}	:	line capacitances of the two signal lines respectively
C_{12}	:	capacitive coupling between the two adjacent signal lines

Uniform, matched impedance lines in homogeneous dielectric media exhibit inductive and capacitive couplings of the same magnitude. Therefore, the opposite polarity noise levels cancel each other, resulting in a zero Differential Far End crosstalk. In homogeneous dielectric media

$$K_L = K_C$$

The problem is, however, that multiconductor cables, twisted pairs or conventional flat cables do not have and for practical reasons cannot have homogeneous insulation for the cross-section of their entire field of propagation. Part of this field extends beyond the solid dielectric into the surrounding air, by that affecting the capacitive coupling considerably while leaving the inductive coupling unchanged. The resulting difference between the opposite polarity coupling coefficients creates the Differential Far End crosstalk. In twisted pairs and conventional flat cables

$$K_L \neq K_C$$

In order to measure and study the parameters of the capacitive coupling coefficient in homogeneous media,

an artificial cable was built with air dielectric. It consisted of five 1/4 inch diameter brass rods 12 feet long, uniformly and parallel spaced. To keep the spacing uniform 1/16 inch thick boards held the rods at two feet intervals. The ground-signal-ground conductor assignment, with 0.312 inch center distance between the rods, established two adjacent uniform signal transmission lines. The characteristic impedance for each line was 50 ohms. To minimize the effect of any object on the TEM field of these artificial air lines, strings held the structure suspended from the ceiling. (Figure 4).

Capacitance was measured for each signal line to the common ground (C_{11} and C_{22}) and between the two signal lines (C_{12}). For results see Table I Condition A.

For crosstalk measurements the two air dielectric transmission lines (50 ohm characteristic impedances each) were terminated with BNC connectors. A 1.0 nanosecond rise time pulse was introduced into the Active signal line, while the Quiet signal line was terminated with a 50 ohm load at the input end. A two channel oscilloscope provided both 50 ohm terminations at the output end. The Active signal line was fed to channel I of the scope through a 20 dB attenuator pad, while the Quiet signal line was connected to channel II straight through. The Far End crosstalk picture on Figure 5 shows the injected pulse edge and the measured 1/2 percent negative Differential crosstalk. (The Active and Quiet line scale ratio is 100:1).

This picture in itself proves the theory: in homogeneous dielectric the Far End crosstalk is practically zero. It is interesting, however, to analyze this 1/2 percent Differential crosstalk and see whether the negative spike really does represent a smaller value for K_C compared to K_L.

For experiment, C_{12} was increased by the manipulation of two BNC receptacle connectors. The BNC connectors were placed on the top of the artificial air dielectric transmission lines. The center contacts of both receptacles touched the center ground brass rod, while the receptacle flanges were in contact with the Active and Quiet signal rods respectively. With this manipulation K_C was increased as shown in Table I Condition B and the Far End Differential crosstalk decreased to 0.1 percent. (Figure 6) For the ideal K_C value of 50 ohm characteristic impedance signal lines this was the best condition achieved by refining the overall alignment and matching the impedance of the test assembly.

In the next experiment the value of K_C further was increased by manipulating with four BNC receptacles in a similar manner as in Condition B. The Far End crosstalk picture (Figure 7) shows 0.6 percent positive crosstalk spike indicating that in this particular case K_C was larger than K_L . The measured capacitance values prove this in Table I Condition C.

Utilizing the artificial air-line structure, K_C values were established for other characteristic impedances. These results are shown in Table II and the graph in Figure 8 is based on these measurements.

<u>Far End Crosstalk In Conventional Multiconductor Cables</u>

The balance between the inductive and capacitive coupling coefficients cannot be maintained in conventional twisted pairs or flat cables.

The insulation material, having the same permeability as the air, does not affect the line inductance or mutual inductance; consequently K_L will not change compared to the values in homogeneous dielectric media. The permittivity of insulation, however, is higher than air and it does affect the line capacitance and the mutual capacitance, both in different proportions. The geometry of conventional multiconductor cables as shown on Figure 9a, helps to visualize that the larger portion of the self capacitances (C_{11}, C_{22}, etc.) is established within the solid dielectric material, while the greater portion of the mutual capacitance (C_{12}) will still be in the surrounding air.

In other words the cable insulation in twisted pairs and in conventional flat cables will increase the self capacitance more than it will the mutual capacitance. Because of this, the value of ideal K_C ratio that is characteristic for homogeneous dielectrics will be decreased. In twisted pairs and conventional flat cables

$$K_C < K_L$$

K_L being the greater, the polarity of coupled noise will show an inductive effect. The K_L component does propagate in the forward direction with an opposite polarity to the inducing current. A positive transient in the Active line will result in a negative Differential crosstalk spike at the Far End of an adjacent Quiet line. Far End crosstalk is the summation of the differences between the

inductive and capacitive coupled voltages, increasing continuously along the length of the line ($\sum_0^{\ell} e_C - e_L$) in conventional cables.

Far End Crosstalk Control By The Dual Dielectric Phenomenon

An improved cable has to correct the K_C deficiency of conventional cables. This design must increase C_{12} because in conventional cables the mutual capacitance is too low compared to the self capacitances. Trying to solve the problem by increasing the cable thickness to the point where the total field of coupling would be confined within a uniform solid dielectric material would result in a cable with impractical dimensions. A practical arrangement is offered by the UNI-FIELD "Black Magic™" type cables. With this type design the value of mutual capacitance can be increased to the optimum condition within the attractive physical features of flat cables.

This arrangement employs an all around jacket over a central cable core, where the dielectric constant of the jacket has a higher dielectric constant than the cable core. (Figure 9b).

The central cable core has excellent dielectric properties and comprises the majority of the fields attributed to the individual signal transmission lines. The coupled fields are affected to a greater extent by the higher dielectric constant jacket material. The correct geometry of the insulation materials in relationship to the conductor arrangement, can offer the ideal conditions known to exist only in homogeneous media. This is the basic principle of the UNI-FIELD "Black Magic™" flat cables.

In order to prove this theory and make comparison to the conclusion from the artificial transmission line measurements, a special "Black Magic™"cable (CA-551) was built with round wire conductors. The pitch/diameter ratio was selected to be (2). The measured capacitances in CA-551 resulted in 5.42 K_C value (Table II), that is only slightly greater than the 5.32 measured on the air dielectric transmission line with the same pitch/diameter ratio.

The jacket of CA-551 cable was then removed leaving the polyethylene flat cable core (CA-550) uncovered. Remeasuring the capacitances the computed K_C value was 4.0 which is small compared to the ideal 5.32.

Crosstalk measurements should prove the theory for the dual dielectric phenomenon. By expectation CA-550 conventional cable should show a high negative polarity Differential crosstalk accumulated at the cable output, while CA-551 "Black Magic™" cable should decrease or eliminate this type of noise.

Oscilloscope pictures were taken of Far End crosstalk on both CA-550 and CA-551 cables: 10 foot cables carried 1.0 nanosecond rise time pulses while 0.18 nanosecond pulse edges were introduced into the 20 foot cables. The polarity of these pulse transients were positive, so the polarity of the Differential crosstalk due to K_C deficiency, were expected to be negative. Figures 10 and 11 identify Far End crosstalk as measured.

The effect of the dual dielectric phenomenon in controlling the negative polarity Differential crosstalk is pinpointed by summarizing the results in the tabulated form below:

TEST CABLE		PULSE RISE TIME Nsec.	(-) DIFFERENTIAL CROSSTALK AT QUIET LINE %	TYPE OF CABLE
No.	LENGTH FEET			
CA-550	10	1	7.6	Conventional
CA-551	10	1	0.4	Black Magic
CA-550	20	0.18	15.0	Conventional
CA-551	20	0.18	0.0	Black Magic

Summary

It has been shown that the inductively coupled voltage exceeds the capacitively coupled voltage in ordinary flat cables. It has been explained that excessive inductive coupling causes Differential Far End crosstalk. It has been proven that by increasing the capacitive coupling the Differential crosstalk can be reduced practically to zero. It has been shown how Differential crosstalk reduction is accomplished in the UNI-FIELD "Black Magic " type cables by the dual dielectric phenomenon.

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2 - Arvanitakis N.C., Kolias J.T., Radzelovage W., Coupled Noise Prediction In Printed Circuit Boards For A High Speed Computer System. IECP, 1966 WESCON.

Table I — Capacitance measurements on Artificial Air Lines, 12 feet long; C in picofarads; five brass rod conductors 1/4 inch diameter, ground-signal-ground alternating, all grounds common, lines terminated to BNC receptacles at both ends.

CONDITION	PITCH/DIA.	$(C_{11}\ C_{22})^{\frac{1}{2}}$	C_{12}	K_C, %	DIFFERENTIAL CROSSTALK, %
A	1.25	265.1	6.44	2.37	- 0.5
B	1.25	267.5	6.72	2.45	- 0.1
C	1.25	269.9	7.06	2.55	+ 0.6

Table II — Capacitance measurements on Artificial Air Lines, 12 feet long; C in picofarads; five brass rod conductors 1/4 inch diameter, ground-signal-ground alternating, all grounds common.

PITCH/DIA.	$(C_{11}\ C_{22})^{\frac{1}{2}}$	C_{12}	K_C, %
2	128.95	7.216	5.32
4	80.05	6.628	7.61
6	66.73	6.050	8.31

Table III — Capacitance measurements on 10 feet long Dual Dielectric UNI-FIELD "Black Magic " flat cable with and without jacket; AWG 28 copper conductors, ground-signal-ground alternating, all grounds common.

STRUCTURE NUMBER	PITCH/DIA.	$(C_{11}\ C_{22})^{\frac{1}{2}}$	C_{12}	K_C, %	CONDITION
CA-550	2	236	9.84	4.00	Without Jacket
CA-551	2	252	14.43	5.42	Jacketed

Mr. Marshall is Director of Research and has been associated with Ansley Electronics Corporation for the past twelve years.

He is an electrical engineer by profession, was born and educated in Hungary, came to the United States in 1957. Since then he has been working in the field of electrical interconnections, cables, connectors, coaxial devices.

Mr. Marshall holds several patents, has presented many papers. His latest contribution is a chapter on "Formed High Frequency Circuits" that has been included in "Handbook of Wiring, Cabling and Interconnecting for Electronics"; the book is being published by McGraw Hill this year.

Mr. Linville joined the Ansley laboratory and research staff in 1967 after retirement from U.S.Air Force as Major. During this time he has been working closely with Joseph Marshall.

Mr. Linville's last military duty was Base Communications Officer at McGuire Air Force Base. Prior to that he taught at the Air Force Communications school and the Navigation school. Military assignments also included Korea and World War II. Educational studies have been at University of Missouri, University of Southern Mississippi, University of Alaska and Villa Nova University, as well as various military schools.

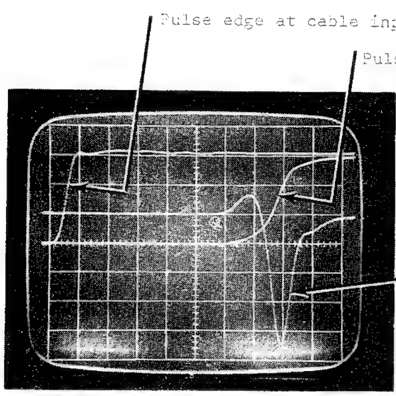


Figure 2 - Oscilloscope picture of Differential crosstalk on conventional 10 foot long multi-signal cable.
Input pulse rise time : 1 nsec.
Horizontal scale : 2 nsec./Division
Vertical scale for Input pulse : 2 V/Div.
Vertical scale for crosstalk : 0.2 V/Div.
Differential crosstalk = 14%

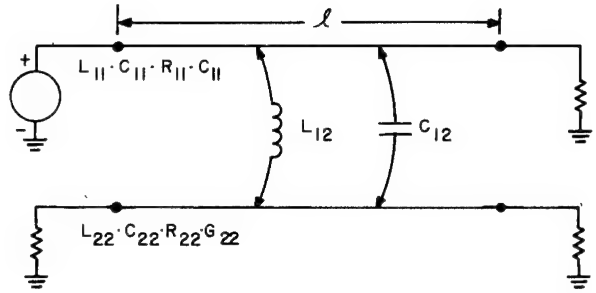


Figure 3 - Coupled transmission lines.

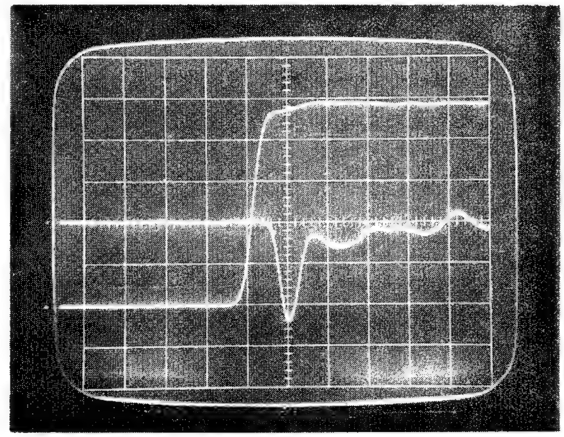


Figure 5 - Far End crosstalk in artificial, air dielectric transmission lines, terminated, 12 feet long.
Condition per Table IA : $K_C < K_L$
Voltage ratio of Active and Quiet lines: 100
Horiz. scale : 2 nsec./Div.
(Location of crosstalk trace slightly shifted for clearer view.)

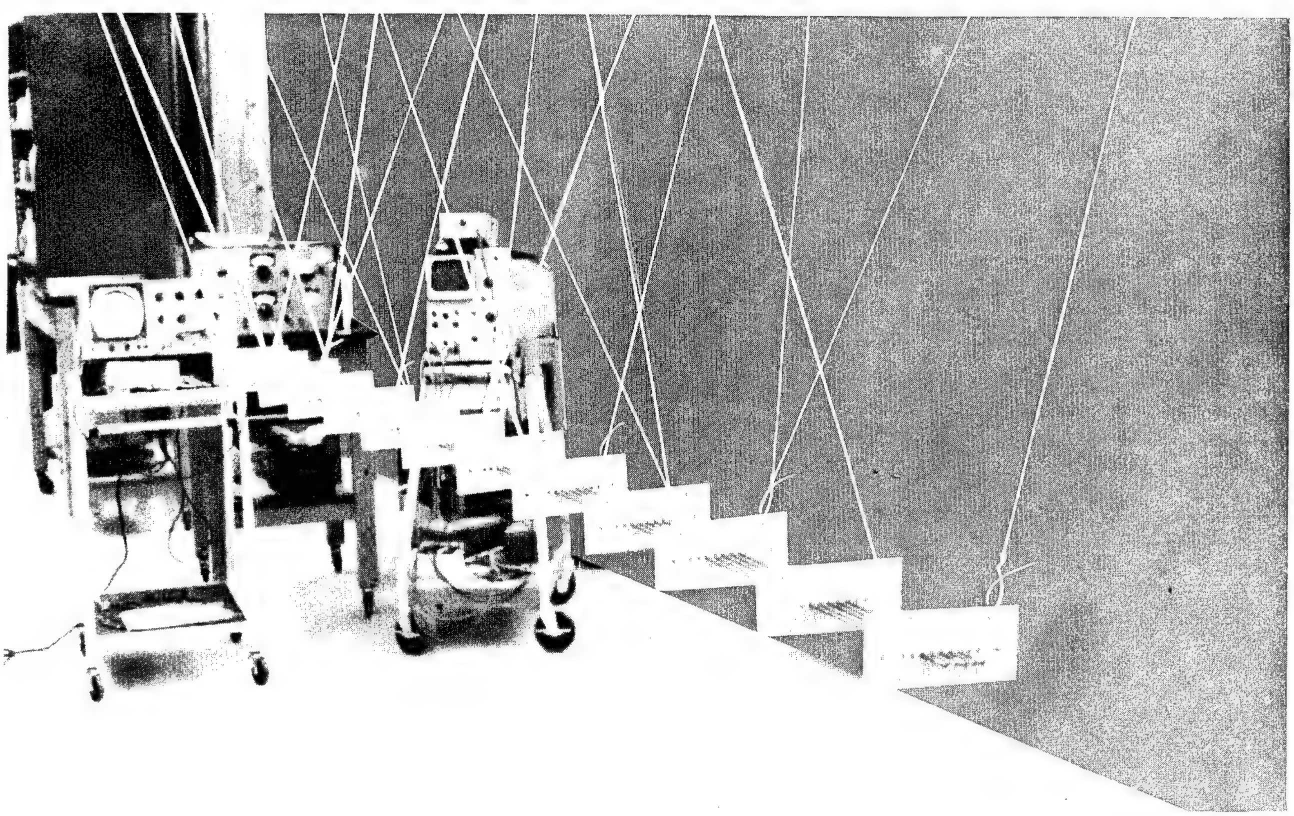


Figure 4 - Laboratory set up of artificial air dielectric cable, 12 feet long.

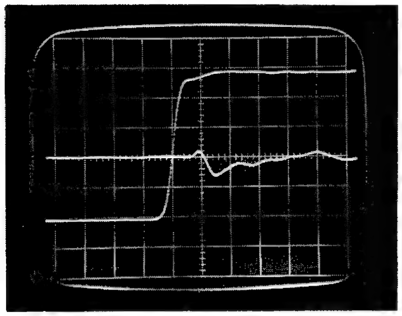


Figure 6 - Far End crosstalk in artificial, air dielectric transmission lines, terminated, 12 feet long.
Condition per Table IB : $K_C \simeq K_L$

Voltage ratio of Active and Quiet lines : 100
Horiz. scale: 2 nsec./Div.
(Location of crosstalk trace slightly shifted for clearer view.)

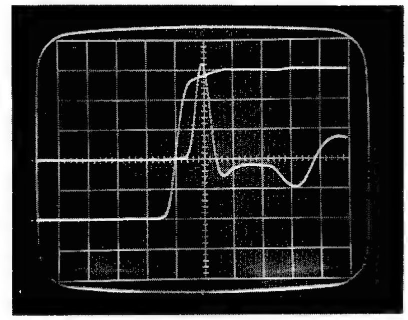


Figure 7 - Far End crosstalk in artificial, air dielectric transmission lines, terminated, 12 feet long.
Condition per Table IC : $K_C > K_L$

Voltage ratio of Active and Quiet lines: 100
Horiz. scale : 2 nsec./Div.
(Location of crosstalk trace slightly shifted for clearer view.)

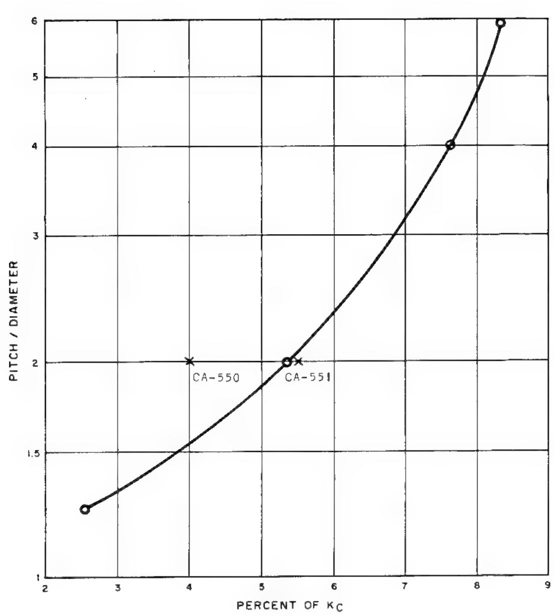


Figure 8 - Graph for the percent value of capacitive coupling coefficient (K_C) vs. Pitch/Diameter ratio in multisignal transmission lines in homogeneous media. (All conductors are diameter shaped with ground-signal-ground sequence).

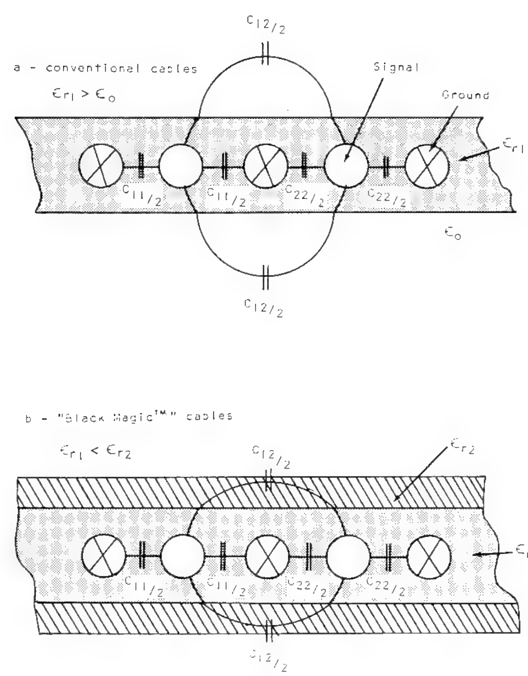
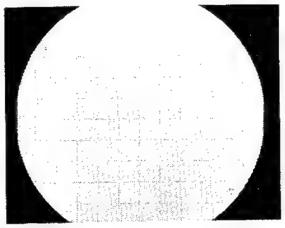


Figure 9 - Simplified representation of self and mutual capacitances in multisignal transmission lines.

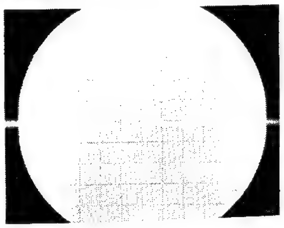


Conventional cable

Figure 10a - CA-550 10, feet long
t_r = 1 nanosecond

Horiz. scale : 2 nsec./Div.

Vertical sacle : 1% crosstalk/Div



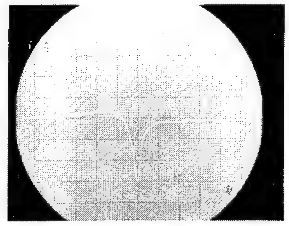
"Black Magic™" cable

Figure 10b - CA-551 cable, 10 feet long
t_r= 1 nanosecond

Horiz. scale : 2 nsec./Div.

Vertical scale : 1% crosstalk/Div

Figure 10 - Differential Far End crosstalk in conventional vs. "Black Magic™" multisignal flat cables.
No. of Active lines : 1
Conductor arrangement : ground-signal-ground-signal, etc.
All conductors are AWG 28, diameter shaped.

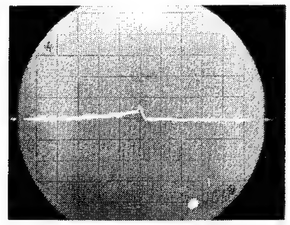


Conventional cable

Figure 11a - CA 550, 20 feet long
t_r= 0.18 nanosecond

Horiz. scale : 2 nsec./Div.

Vertical scale: 5% crosstalk/Div.



"Black Magic™" cable

Figure 11b - CA-551 cable, 20 feet long
t_r= 0.18 nanosecond

Horiz. scale : 2 nsec./Div.

Vertical scale: 5% crosstalk/Div.

Figure 11 - Differential Far End crosstalk in conventional vs. "Black Magic™" type multisignal flat cables.
No. of Active lines : 1
Conductor arrangement: ground-signal-ground-signal, etc.
All conductors are AWG 28, diameter shaped.

TEMPERATURE CYCLING INSTABILITY OF SOLID DIELECTRIC SEMI-RIGID COAXIAL CABLE

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Abstract:

Accelerated temperature cycling tests of solid dielectric semi-rigid coaxial cable cause drastic changes in cable dimensions.
The results demonstrate a need for alternate designs that offer performance stability under conditions of continuing temperature variation.

INTRODUCTION

The purpose of this paper is to present data on the dimensional changes of 1/4 inch solid dielectric semi-rigid coaxial cable caused by thermal cycling and, based upon the data, submit conclusions and recommendations covering:

1. Temperature cycling versus steady state temperature immersion.
2. The need for more realistic temperature limits in current specifications and vendors catalogs.
3. The advisability of changing to air-articulated designs.

The original prime objective of the temperature cycling test was to determine a method of prestabilizing the thermal-cycling dimensional effects on solid dielectric cable before making the final connector assembly.

DATA

The test samples consisted of TFE Teflon solid dielectric cable, 50 ohm impedance, with an overall diameter of 0.250 inch. Both inner conductor and outer conductor were aluminum. Length and diameter measurements were made before temperature exposure. Monitoring during cycling was primarily limited to length measurements. After completion of cycling, length and diameter measurements were repeated.

The prime objective of the temperature cycling test was to accelerate dimensional changes of the teflon dielectric in order to determine if and when stabilization is reached. Table I tabulates measurements made during 20 temperature cycles.

The prime objective of the exposure to the 24 hour elevated temperature which preceded temperature cycling was to determine the degree of pre-stabilization accomplished by first immersing the cable in a high temperature environment. Table II is a tabulation of these results. As was done previously, measurements were made of not only the dielectric, but also the inner and outer conductor.
Figure 1 identifies the total test plan. Figure 2 identifies the time sequence and temperatures used for the temperature cycling. Figure 3 is a plot of dimensional changes of the dielectric and the inner conductor versus the number of temperature cycles.
Figure 4 consists of two photos of cable ends, demonstrating the degree of shrink-back of the dielectric and the inner conductor. Figure 5 contains two x-rays of the same cable, demonstrating that the inward movement of the center conductor is not due to its being distorted internally.
Questions have been raised pertaining to the applicability of the temperatures used in this evaluation to normal cable usage. Although the temperature extremes selected were specifically determined for the Pioneer program, it should be recognized that the temperature span of 250 degree C (+93 degree C to -157 degree C) is approximately the same as the temperature span obtained by the maximum and minimum temperature rating----- +200 degree C to -55 degree C.

SUMMARY OF TEST RESULTS

The following effects of temperature cycling were noted:

1. Continuing linear shrinkage of the dielectric.
2. Increased outside diameter of the outer conductor, maximum at the center.
3. Linear shrinkage of the inner conductor.

Short duration temperature cycling causes a much greater dimensional change than prolonged immersion.

CONCLUSIONS

1. Present specification temperature limits may be satisfactory for steady-state limits. They are not satisfactory for temperature cycling.
2. The inner and outer conductors are cold-worked by the dielectric.
3. The tests failed to develope a temperature immersion method of pre-stabilizing solid dielectric semi-rigid coaxial cable.

RECOMMENDATIONS

1. Establish realistic temperature limits in applications requiring periodic temperature excursions.
2. Specify high strength inner and outer conductors where applications require periodic temperature excursions.
3. Specify air-articulated dielectrics where applications require large and periodic changes in temperature.

Acknowledgement:

This paper is primarily based upon work done by Mr. A. Kamensky, a colleaque at TRW Systems, Redondo Beach, California.

Biography:

Arnold J. Daniels received his BS degree in Communication Engineering from The University of Wisconsin in 1947. He has specialized in the field of wire and cable since 1949. He is currently working on the cabling of the DD and the LHA ships for the Ingalls Shipbuilding Division of Litton Industries.

TABLE 1 DIMENSIONAL CHANGES DUE TO THERMAL CYCLING

TEST	TEST	INITIAL	DIMENSIONS AFTER THERMAL CYCLE, (1) INCHES						COMMENTS
Points	Specimen I.D. No.	Dimensions (Inches)	3	4	5	9	14	20	
Outer Conductor Length	1 (2)	18.120			18.104	18.104	18.096	18.045	Outside Conductor Shrunk 0.025 inch
	3 (3)	17.965			17.950	17.941	17.938	17.937	Outside Conductor Shrunk 0.028 inch
	6	20.033			20.015	20.008	20.000	19.997	Outside Conductor Shrunk 0.037 inch
	9	20.017			19.998	19.994	19.987	19.975	Outside Conductor Shrunk 0.042 inch
	10	20.037			20.012	20.008	20.000	20.000	Outside Conductor Shrunk 0.042 inch
Change in Length of Teflon Relative To Outer Conductor	1		-0.168	-0.206	-0.229	-0.346	-0.429	-0.500	Teflon Shrunk 0.525 inch
	3		-0.164	-0.216	-0.233	-0.349	-0.427	-0.472	Teflon Shrunk 0.500 inch
	6		-0.274	-0.318	-0.367	-0.545	-0.659	-0.734	Teflon Shrunk 0.771 inch
	9		-0.222	-0.279	-0.322	-0.495	-0.619	-0.689	Teflon Shrunk 0.731 inch
	10		-0.303	-0.375	-0.422	-0.586	-0.690	-0.768	Teflon Shrunk 0.805 inch
Change in Length of Center Conductor Relative To Outer Conductor	1				-0.112	-0.185	-0.262	-0.336	Internal Conductor Shrunk 0.361 inch
	3				-0.115	-0.178	-0.253	-0.325	Internal Conductor Shrunk 0.351 inch
	6				-0.156	-0.244	-0.351	-0.439	Internal Conductor Shrunk 0.476 inch
	9				-0.159	-0.244	-0.343	-0.434	Internal Conductor Shrunk 0.476 inch
	10		-0.094	-0.108	-0.134	-0.212	-0.305	-0.390	Internal Conductor Shrunk 0.427 inch
Outside Diameter of the Outer Conductor, Measurements Taken at the Ends or the Center of the Cable as Indicated	1 end	0.2508			0.2530	0.2532	0.2532	0.2532	
	1 center	0.2508			0.2523	0.2534	0.2538	0.2545	
	1 end	0.2508			0.2522	0.2526	0.2526	0.2528	
	3 end	0.2508			0.2528	0.2528	0.2528	0.2528	
	3 center	0.2508			0.2528	0.2532	0.2542	0.2546	
	3 end	0.2508			0.2529	0.2532	0.2534	0.2534	
	6 end	0.2508			0.2520	0.2532	0.2532	0.2538	
	6 center	0.2508			0.2537	0.2538	0.2538	0.2556	
	6 end	0.2508			0.2534	0.2537	0.2534	0.2536	
	9 end	0.2508			0.2527	0.2526	0.2526	0.2526	
	9 center	0.2508			0.2524	0.2534	0.2547	0.2556	
	9 end	0.2508			0.2528	0.2528	0.2528	0.2527	
	10 end	0.2508			0.2517	0.2518	0.2519	0.2526	
	10 Center	0.2508			0.2528	0.2536	0.2546	0.2552	
	10 end	0.2508			0.2518	0.2518	0.2522	0.2527	
	Ave.	0.2508			0.2526	0.2530	0.2533	0.2537	Average Diameter of Cable Increased by 0.0029 inch

(1) Thermal Cycle: +200 degree F, (+93 degree C) 15 minutes
Room temperature 15 minutes
-250 degree F, (-157 degree C) 15 minutes
Room temperature 15 minutes

(2) Specimens 1 and 3 were taken from the same cable

(3) Specimens 6, 9, and 10 were taken from the same cable, but different from one in note (2).

TABLE 2 - DIMENSIONAL CHANGES DUE TO THERMAL AGING AND CYCLING

MEASURE-MENTS	TEST SPECI-MEN I. D.	AMBIENT DIMEN. INCHES	DIMENSIONS DURING THERMAL AGING (at 200 degree F), INCHES					SPECIMEN STABILIZ-ED at R.T IN.	DIMENSIONS AFTER THERMAL CYCLING (3) INCHES				TOTAL SHRINKAGE
			1 hr.	2 hr	4 hr	8 hr	24 hr		2 CYCLES	4 CYCLES	6 CYCLES	8 CYCLES	
Outer Conductor Length	2 (1)	17.934	Not Measured					17.922	17.910			17.905	0.029 inch
	4 (2)	19.978	Not Measured					19.968	19.955			19.945	0.033 inch
	5 (1)	17.940	Not Measured					17.922	17.915			17.908	0.032 inch
	7 (2)	20.033	Not Measured					20.015	20.007			19.992	0.041 inch
	8 (2)	20.017	Not Measured					20.000	19.987			19.987	0.030 inch
Change in Teflon Relative to Outer Conductor	2		+0.024	+0.026	+0.038	+0.040	+0.040	-0.072	-0.265	-0.303	-0.343	-0.359	0.388 inch
	4		+0.023	+0.024	+0.037	+0.042	+0.043	-0.067	-0.362	-0.426	-0.487	-0.524	0.557 inch
	5		+0.022	+0.024	+0.038	+0.036	+0.036	-0.085	-0.210	-0.278	-0.325	-0.350	0.382 inch
	7		+0.021	+0.023	+0.035	+0.036	+0.034	-0.081	-0.335	-0.412	-0.474	-0.522	0.563 inch
	8		+0.021	+0.022	+0.033	+0.038	+0.038	-0.093	-0.336	-0.419	-0.479	-0.550	0.580 inch
Change in Center Conductor Relative to Outer Conductor	2		Not Measured (no visual change)					+0.019	-0.029	-0.080	-0.116	-0.150	0.179 inch
	4		Not Measured (no visual change)					+0.017	-0.042	-0.104	-0.153	-0.197	0.230 inch
	5		Not Measured (no visual change)					+0.013	-0.026	-0.072	-0.110	-0.144	0.230 inch
	7		Not Measured (no visual change)					+0.014	-0.037	-0.090	-0.133	-0.190	0.231 inch
	8		Not Measured (no visual change)					+0.019	-0.027	-0.088	-0.137	-0.182	0.212 inch
Change in Outside Diameter of Cable	2 edge	.2508	Not Measured					.2517	.2534			.2534	
	2 cen	.2508	Not Measured					.2520	.2538			.2539	
	2 edge	.2508	Not Measured					.2524	.2539			.2543	
	4 edge	.2508	Not Measured					.2519	.2529			.2544	
	4 edge	.2507	Not Measured					.2522	.2528			.2543	
	4 edge	.2508	Not Measured					.2516	.2526			.2539	
	5 edge	.2508	Not Measured					.2520	.2539			.2546	
	5 cen	.2508	Not Measured					.2521	.2527			.2537	
	5 edge	.2507	Not Measured					.2517	.2538			.2536	
	7 edge	.2507	Not Measured					.2518	.2533			.2539	
	7 cen	.2507	Not Measured					.2518	.2527			.2539	
	7 edge	.2507	Not Measured					.2523	.2543			.2552	
	8 edge	.2506	Not Measured					.2518	.2539			.2538	
	8 cen	.2505	Not Measured					.2519	.2528			.2539	
	8 edge	.2507	Not Measured					.2519	.2543			.2543	
	AVE	.2507						.2519	.2534			.2541	Ave. Dia. of Cable Incr. 0.0034-in.

(1) Specimens 2 and 5 were taken from same cable
(2) Specimen 4, 7 and 8 were taken from same cable, but different from note (1)
(3) Thermal Cycle: +200 degree F 15 minutes
R. T. 15 minutes
+250 degree F 15 minutes
R. T. 15 minutes

FIGURE 1. TEST PLAN

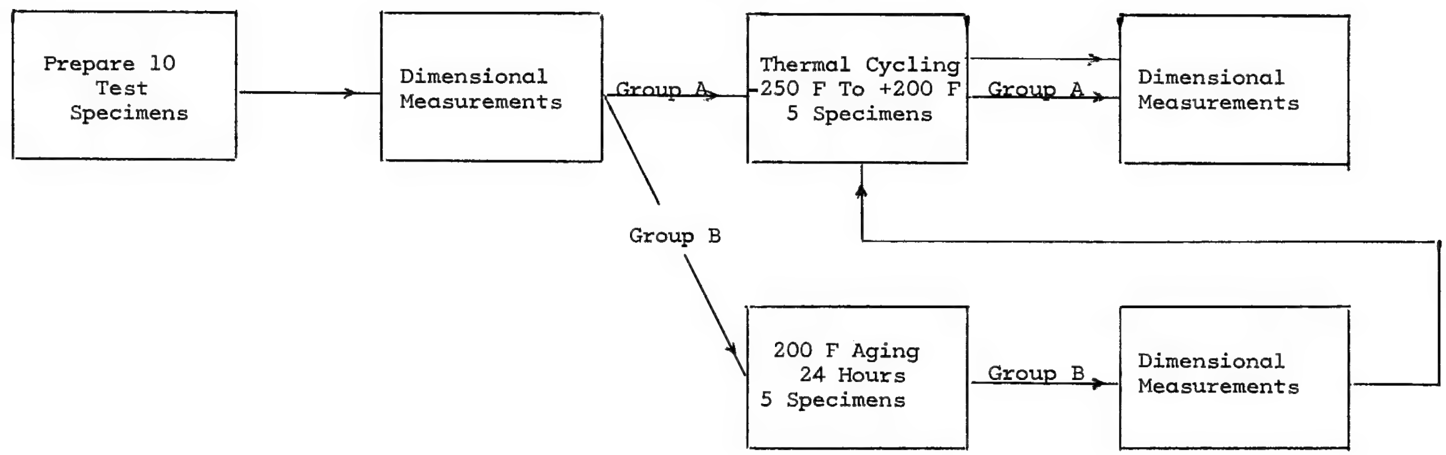


FIGURE 2.
TEMPERATURE CYCLING SCHEDULE

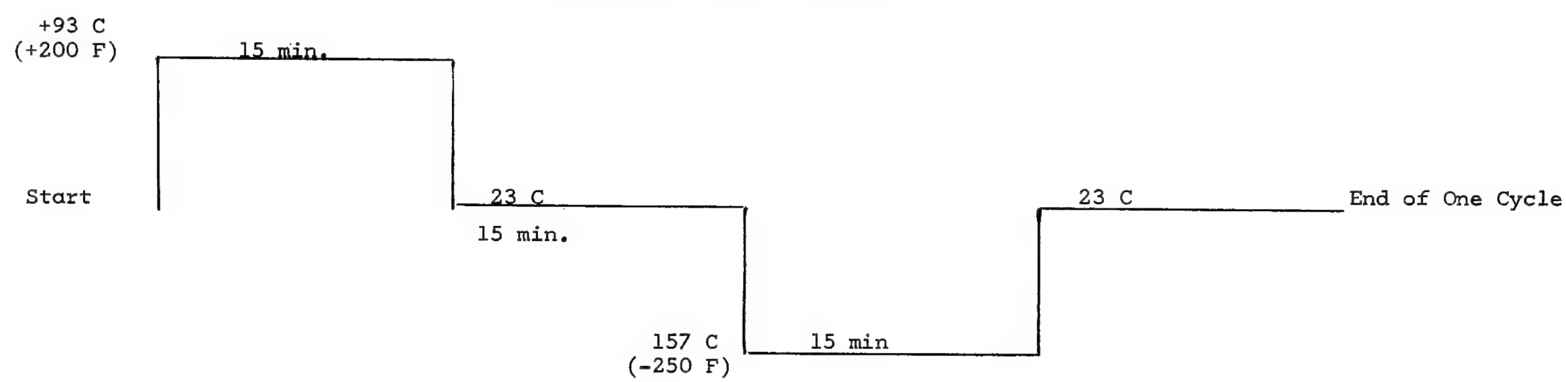
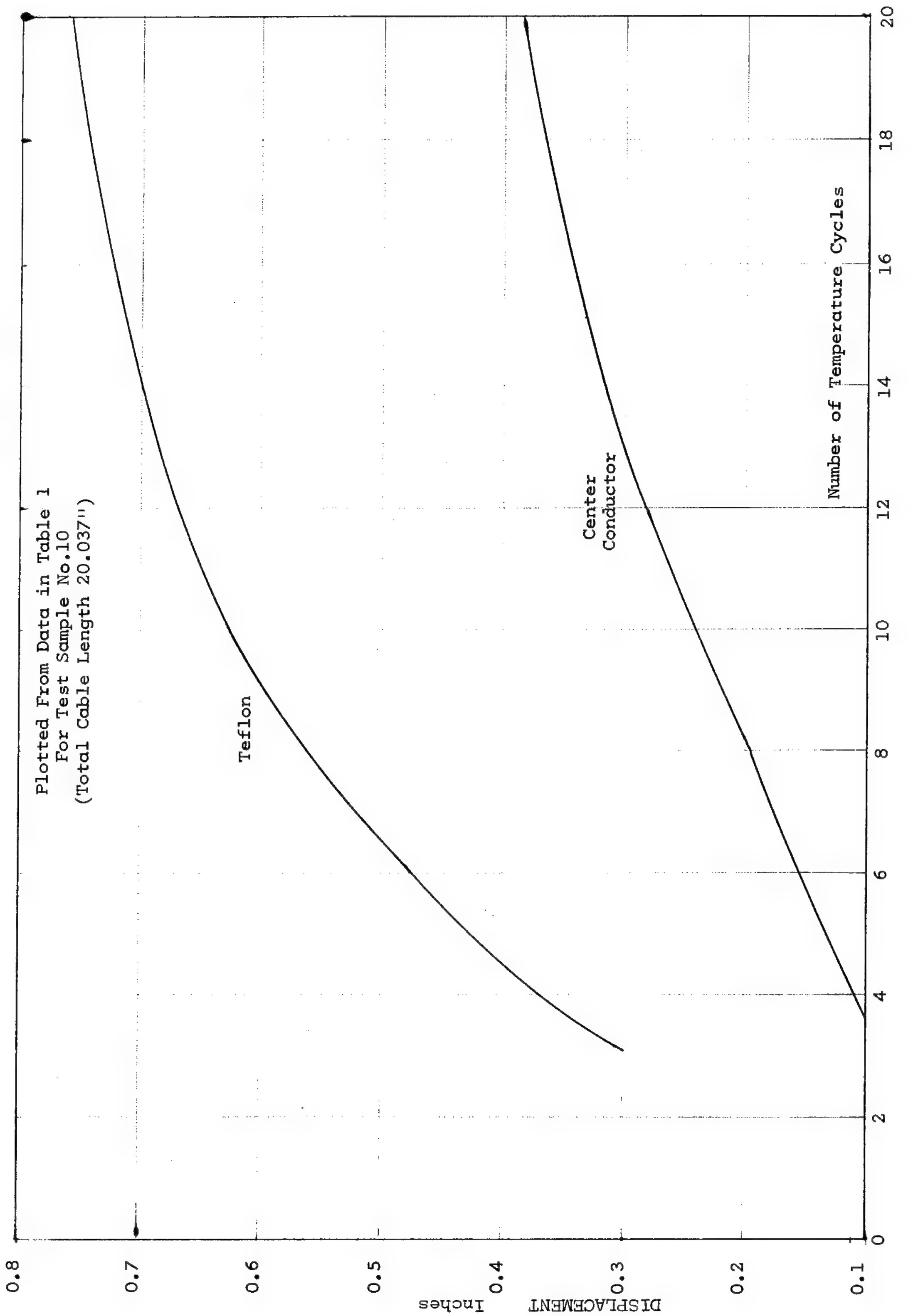
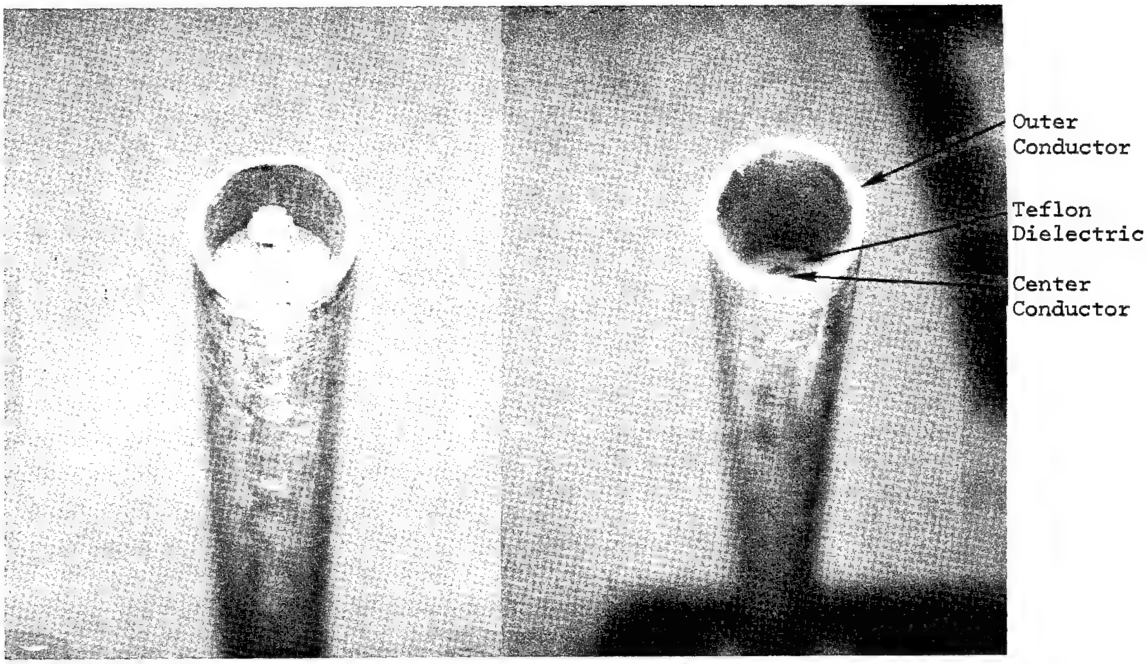


FIGURE 3 ACTUAL SHRINKAGE VS NUMBER OF TEMPERATURE CYCLES





(a) One end of cable shows center and outer conductors flush while Teflon has shrunk 0.203 inch.

(b) The opposite end of the cable shows Teflon has shrunk 0.565 inch and center conductor has shrunk 0.390 inch.

FIGURE 4. Photograph shows linear shrinkage of Teflon dielectric and center conductor on test specimen No. 10.

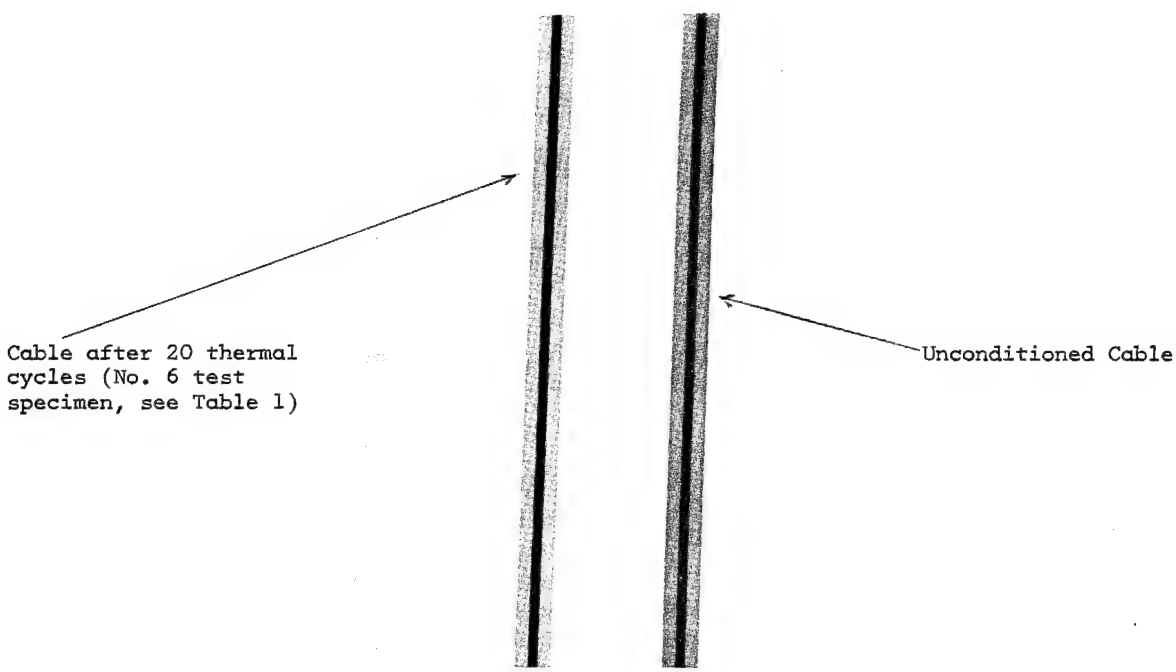


FIGURE 5. Radiograph shows no wave formation of center conductor after thermal cycling.

LIGHTNING PROTECTION OF BURIED COAXIAL CABLES

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SUMMARY

On a buried cable 150 meters long, measurements were made of voltages occurring across the plastic jacket when currents simulating lightning strokes are discharged into the soil. The comparison between the values measured in absence with those measured in presence of one or two shield wires shows that one shield wire is sufficient to insure good protection. For long cables in unfavorable soils, voltages comparable with those measured on the experimental installations are expected, according to suitable calculations.

1. INTRODUCTION

During the decade 1959-1968 statistical information was collected about the faults occurred on the coaxial cables of the Italian telephone network which extended from 5450 km in 1959 to 6615 km in 1968.

By working out the average over the full decade we find that the total number of faults per 100 cable km/year is 7.85, whilst the number of faults per 100 cable km/year due to lightning troubles is 1.50.

The lightning troubles constitute therefore a high percentage (19%) of the total number of faults.

In 1969, at the time when an important programme of coaxial cables was being carried out, the technical and economical situation was altogether different from the one of the previous decade. The cost of the cables (even at constant monetary value) had raised because of the greater number of coaxial pairs and the commercial efficiency had also grown owing not only to the increase in the number of the coaxial pairs contained in one cable, but also to the considerably increased number of communications transmitted on each coaxial pair.

Such considerations led to the adoption of new criteria in the choice of routes and to new methods of laying the cables (routes mostly along highways, increased laying depth along routes off the highways, protections by means of cement ducts) which would involve a noticeable reduction in mechanical faults.

In addition, the adoption of a polyethylene insulating sheath, much more effective than the PVC one previously used on the first coaxial cables, would involve the disappearance of the faults due to corrosion.

Taking into account the above mentioned reduction of the faults due to mechanical and chemical reasons, it is clear that the percentage of faults due to lightning troubles (on the total number of faults) would increase if special protections are not adopted also in this respect.

2. LIGHTNING PROTECTION BY MEANS OF SHIELD WIRES

Shield wires laid some inches above buried telephone cables for lightning protection purposes are extensively used in U.S.A. since many years. Recently their use has been gaining larger and larger confidence also in some European Countries.

Bearing this in mind, it was in principle decided to protect the cable against lightning troubles by means of a 8 mm (.32") galvanized steel rod, to be buried above the cable at a distance of about 30 cm (12") from it.

In order to determine the efficiency of the galvanization protecting the steel rod against corrosion, tests were carried out on several types of galvanized rod.

The tests consisted in winding the full length of some samples around a mandrel having 80 mm (3.2") diameter and subsequent straightening up followed by dipping the samples in a solution containing 36% of copper sulphate and having a density of 1.186.

Each immersion had a duration of 1 minute; the immersions were repeated until evidence of corrosion appeared.

The type of rod chosen is that on which very slight traces of corrosion appeared after 8 immersions.

Photographs No. 1 to No. 6 illustrate some of the phases for the installation and the soldering of the steel rod.

3. PLANNING THE FIELD EXPERIMENTS

In the Countries where the shield wires are used a favourable experience has so far been gathered, however it is only of a rough statistical nature : it was therefore thought advisable to carry out systematic field experiments in order to assess, on the ground of suitable numerical values, the actual degree of safety connected with the use of shield wires.

The aim of the field experiments is, basically, that of comparing the numerical values of the voltages across the polyethylene jacket, measured in a first step without and in a second step with one (or two) shield wires, when a current equal to the lightning strikes the ground in proximity of the cable and spreads in all directions from the point of the stroke. If the voltage is linearly proportional to the current and the breakdown electrical stress of the jacket (characterized by increased thickness in comparison with those used where there is no danger of lightning troubles) is known, the actual breakdown voltages for both the steps can easily be calculated and compared.

Mountain regions are of special importance because there the soil has usually high electrical resistivity and therefore the voltages between the earth and the metallic sheaths of the cables are higher than in lowlands; however, surge generators are usually not available there. Unfortunately, most electrical laboratories, where high voltage tests can be carried out, are located in close proximity to large towns, where the soil is generally characterized by low electrical resistivity. Due to these practical reasons one is obliged to carry out the tests in environments where the ground has low electrical resistivity and to extrapolate the results, by means of suitable calculations, to the important case of soil having high electrical resistivity.

Moreover, practical reasons do not allow to carry out the field measurements on long cables, as it should be advisable in order to reproduce the actual conditions of buried cables. One must confine the field experiments to the relatively short lengths available inside the laboratories and, again, extrapolate the results to the case of very long cables through suitable calculations.

Another important feature of the experiments is connected with the settlement (as time goes by) of the earth surrounding the cable and the shield wires. As a matter of fact, it is apparent that some months after the laying and backfilling operations the contact between the soil and the shield wires becomes more intimate, so that a larger portion of the lightning current tends to flow along the shield wires and the voltage across the polyethylene jacket is reduced.

It is therefore important to carry out field measurements not only immediately after the laying operations, but also some months later.

The field measurements are significant only when the waveform of the surge currents discharged from the generator into the soil reproduce with acceptable approximation the actual lightning phenomenon.

The peak value of the current must be high enough to allow significant field measurements, but not so high as to involve dangerous conditions for the probes measuring the voltages across the polyethylene jacket.

In order to make the right choice among the laboratory generators, thus avoiding waste of time and money due to the use of unsuitable generators, in a preliminary stage series of calculations were carried out on the basis of the known electrical characteristics of the generators, of the grounding system and of the possible configurations of the circuit of the current strokes.

In Appendix A the calculations carried out for the generator and the circuit con-

figuration finally chosen are summarized.

4. DESCRIPTION OF THE FIELD PLANT

For the purposes of the field experiment reference was made to the cable containing 8 coaxial pairs 2.6/9.5 mm (.375") which at present is largely being installed in Italy.

Taking into account that the measurements concern only the voltages arising between metallic sheath and earth, use was made only of an empty corrugated aluminium sheath covered with a polyethylene jacket of the correct thickness (as previously mentioned, this is suitably increased in comparison with the standard case of cables not exposed to the danger of lightning strokes).

The gap between metallic sheath and plastic jacket is filled with a special bituminous compound in order to prevent corrosion in case of mechanical damages to the jacket during installation or service of the cable. The diameter of the aluminium sheath is approx. 52 mm (2.05") with reference to the peaks of the corrugation, the diameter of the polyethylene sheath is approx. 60 mm (2.35").

Preliminary tests carried out on ten samples, each some meters long, gave the range of the breakdown voltage in case of lightning stroke on the above mentioned polyethylene sheath : using impulses of the type 6/50 μsec, such voltage is between 190 kV and 250 kV (peak value).

The above mentioned cable was buried in a field of the CESI Laboratories in Milan.

In proximity of the cable the electrical resistivity of the soil (ρ) was practically uniform because the cable was laid sufficiently far from any other metallic underground connections. Such resistivity was measured to be in the order of 250 ohm$\cdot$m, with small variations according to the season.

Any effort was made in order to lay a cable as long as possible, but the dimensions of the available field obliged to lay a cable only 150 m (490 ft) long.

The cable is laid in cement conduits at approx. 65 cm (25") depth, thus reproducing the actual laying conditions.

At suitable intervals probes are applied to the cable in order to measure the voltages across the polyethylene sheath.

Fig. 7 schematically shows the actual layout of the cable and the measuring probes, whereas Fig. 8 gives an idea of the general layout of the plant. From Fig. 8 one can clearly see that 8 probes are suitably placed along the cable, in symmetrical positions related to the middle point.

The current strokes coming from a 56 kJ generator, placed approx. 150 m (490 ft) apart, alternatively go to "injection rods" installed at various distances along a line perpendicular to the cable in its middle point, as shown in Fig. 8.

The minimum distance of 5 m (16.5 ft) from the cable depends upon the necessity that, with a current stroke of 4000 A, the voltage measured on the oscillograph alternatively connected to the various probes is not higher than 25 kV in order to prevent their breakdown. As a matter of fact, current strokes of 4000 A are considered to be the minimum value necessary to avoid any doubt about the physical meaning of the field tests.

After having been injected into the soil, the current spreads in all directions and goes to 12 "earthing rods" placed at regular intervals along a circumference having 100 m (305 ft) diameter and centre in the middle point of the cable. The 12 "earthing rods" are electrically interconnected by means of an insulated copper conductor having 95 sq. mm. (188 MCM) cross section. An identical conductor carries the current stroke back to the "earthing plate" of the generator, as shown in Fig. 8.

As far as the shield wires are concerned, the field measurements have been carried out as follows : in a first step without any shield wire; in a second step with one shield wire placed 25 cm (10") above the axis of the cable; in a third step with two shield wires placed 25 cm above the cable and symmetrical to a vertical plane containing the cable axis, as shown in Fig. 7.

A fourth series of measurements, with two shield wires again, was carried out 8 months later in order to check the influence of the natural settlement of the soil through the months following the mechanical "soil compaction" operations carried out immediately after each laying of the cable and shield wire.

5. SHORT SURVEY OF THE MEASUREMENTS CARRIED OUT

5.1. In a first step, series of measure-

ments were carried out in order to check the actual waveform of the current stroke and also to verify whether the correspondent variations of the voltages measured across the polyethylene jacket follow a pattern of linear proportionality. The waveforms of the current strokes, when the 56 kJ generator is used, are shown in Fig. 9 together with the values calculated in Appendix A : it is apparent that the agreement between measured and calculated values is good enough; it is also confirmed that the generator gives rise to a current stroke sufficiently approximating the actual lightning stroke at least in the "wave front", which is the most important part of the whole stroke from the field experiments view point.

The measurements have been carried out using current strokes between 1000 A and 7000 A injected at 25 m (83 ft) from the cable middle point, which is the distance necessary to avoid voltages higher than 25 kV on the measuring probes with the heaviest strokes. One must, in addition, also consider that 25 m are the maximum distance at which, in a first approximation, it is still permissible to assume the current stroke as injected in the centre of a circle having 100 m diameter.

The voltages measured on the polyethylene jacket have been confirmed by these measurements to be linearly proportional to the current strokes : therefore one is allowed to work out the voltages due to strokes of 30 ÷ 40 kA by simple extrapolation from the voltages due to strokes of few kA only.

5.2. In a second step, series of measurements of the voltages due to 4000 A have been carried out, the cable being buried alone (i.e. without any shield wire) and the strokes being injected first at 5 m (16.5 ft), then at 10 m (33 ft), finally at 25 m (83 ft). Some measurements were carried out on all the probes placed symmetrically to the middle point of the cable, some other ones on the probes placed on one side of such middle point; some ones of them have been carried out with both the aluminium sheath ends earthed, thus reproducing the conditions of the actual installations; some other ones with the first end earthed and the second end insulated, for comparison purposes.

These measurements have confirmed that:

a) the variations of the voltage versus distance from the injection point are in accordance with the well known formula by Sunde.[1]

$$V = \frac{\rho}{2\pi r} I$$

with obvious meaning of the symbols;

b) the measured values of the voltages give rise to curves sufficiently symmetrical with respect to the middle point of the cable, therefore the electrical characteristics of the soil can actually be considered sufficiently uniform;

c) when one end of the aluminium sheath is insulated from earth, the voltages measured in proximity of such end are higher than those ones measured near the opposite end, because at the insulated end the voltage wave undergoes complete reflection.

5.3. In a third step, series of measurements of voltages due to current strokes of 4000 A were carried out, the cable being protected by a shield wire consisting of the heavily galvanized steel rod mentioned in par. 2., having 8 mm (.32") diameter, the injection point being at 5 m (16.5 ft) distance.

The ends of the aluminium sheath were both earthed, the shield wire was solidly bonded to the 95 sq. mm. (188 MCM) conductor interconnecting the "earthing rods" where it crossed the circumference having 100 m diameter.

5.4. Similar series of measurements were in succession carried out on the cable protected by means of two shield wires, both immediately after the laying and backfilling operations and 8 months later in order to take into account the natural settlement of the soil when time goes by.

5.5. At last, by means of measurements similar to the ones outlined in 5.1., it was checked that the variations of the voltages are linearly proportional to the currents also when magnetic shield wires are present.

These measurements were carried out using current strokes up to the maximum value of 7000 A.

The basic results of the measurements carried out on the cable without any shield wire, with one shield wire, with two shield

wires, with two shield wires 8 months after the laying and backfilling operations are shown in Fig. 10.

Looking at this figure one can say that the use of one shield wire approximately riduces to 50% the voltage between metallic sheath and surrounding earth; the addition of a second shield wire involves a little improvement in the protection of the cable; at last the settlement of the soil through the time gives rise to a further little improvement. Roughly speaking, one can also say that the conditions related to the cable protected by one shield wire are, after some years, practically the same as with the cable protected by two shield wires immediately after the laying and backfilling operations.

6. APPLICATION OF THE EXPERIMENTAL RESULTS TO THE ACTUAL CABLE LINES

As already mentioned in par. 3., the actual cable lines are usually many kilometers long and the danger of lightning strokes is for them of special importance in mountain regions, where the soil resistivity is high.

From Appendix B one can see that, as far as the cable length is concerned, the values measured on the experimental cable only 150 m long can be used for very long cables without appreciable error.

From Appendix B one can also see that in mountain regions, i.e. in soils with high resistivity, the current flowing in the soil is approximately 10 ÷ 15% lower than in soils having a resistivity as low as that one characterizing the experimental plant. Consequently the voltages across the plastic jacket for cables laid in mountain regions are a little lower than those measured in the experimental plant.

In a first approximation, one can conclude that the voltage values measured on the experimental plant are sufficiently near to those ones which must be expected for long cables in mountain regions, obviously with reference to a same amount of the lightning stroke.

We come finally to a comparison between the safety margins of the new and the old cable network, which has no shield wire and offers lower withstand to lightning breakdown (70 ÷ 100 kV instead of 190 ÷ 250 kV).

Taking into account both Fig. 10 and the well known graph by Sunde (ref. 1 § 9.3), it appears that the average value of the strokes must increase from 30 KA to 120 KA in order to achieve the same amount of faults/year in the new network, where voltages are approximately 50% than in the old network (for a same stroke).

Looking at the above mentioned graph, the actual probabilities of such lightning strokes are in the ratio 50/2.5 : therefore the faults/year due to lightning strokes in the new network are expected to be less than 10% when compared with the old one.

7. PROTECTED INSTALLATIONS ALREADY CARRIED OUT AND OTHERS PLANNED

On 1st September 1972, it appears that 595 km of cable subdivided into three plants of 13, 115 and 467 km respectively, are protected with said galvanized steel rod.

It is anticipated that by 1.11.1972 a further 45 km of shield wire will be installed on two plants now being carried out.

Of course, some years are necessary in order to gather statistical data concerning the cable faults due to lightning strokes on this first part of the new coaxial cables network. Only when such data will be available, we will be in a position to check whether the reduction of the faults/year due to the presence of the shield wire and to the use of a polyethylene jacket of increased thickness agrees with the expected one shown at the end of par. 6.

ACKNOWLEDGEMENTS

The authors wish to thank Industrie Pirelli S.p.A. and Sirti S.p.A. for the permission to publish the present paper.

APPENDIX A

Representative values of lightning currents have peak amplitudes of the order of some tens of KA, rise times of the order of few μs and tails of the order of hundreds of μs.[1-2]

In order to obtain significant measurements, the generating circuit in laboratory should meet two main requirements, namely :

a) obtain a waveform sufficiently representative of lightning;

b) reach a value of current not too far from the real ones since it may be expected that soil is of a non linear nature.

On the other hand measuring apparatuses impose some limits, first of all the voltage on the probes.

From the point of view of waveform, the generator is a charged capacitor; it must be connected to the "injection rod" on the field from inside the laboratory so that the inductance of about 150 meters of line is also present.

Since the soil is mainly a resistance, in first approximation the equivalent circuit of the plant is a series of R,L,C. with a step input of voltage (see Fig.11)*

It is well known that the response of the circuit of Fig. 11, i.e. current I, may be either a dumped sinusoidal or a double exponential waveform depending on the value of the ratio

$$\frac{R}{2}\sqrt{\frac{C}{L}}$$

according to which parameters must be chosen.

In order to obtain a radial field in the soil near the injection point, it is necessary to keep the input conductor very apart from the return conductor; so that it results, for the inductance L, the rather high value of $L \approx 500\ \mu H$.

The generator can be charged at different values of voltage by a suitable connection of its internal capacitors; in this case the total energy is given.

The CESI laboratories had two solutions available, namely :

a) $\frac{1}{2} C E^2 = 56\ KJ \quad E \leq 1\ MV$

b) $\frac{1}{2} C E^2 = 200\ KJ$

Resistance R has a lower value, R_o, which is the resistance in the soil between the "injection rod" and the system of the 12 "earthing rods".

* Note that the generator, which is a capacitor initially charged, is represented with an uncharged capacitor in series with a voltage generator.

Due to ionisation in the soil, R_o is non linear; if a current level of 10 KA is assumed, preliminary calculations give $R_o \approx 30\Omega$, the main contribution being that of the injection point.

The circuit of Fig. 11 has been computed for given values of the step voltage E and of parameters R, C, L, using simplified formulae, which are quite sufficient for design purposes and which stress the main properties of the waveform.

They are :

a) the peak current :

$$I \approx E/R$$

b) rise time or time to peak value :

$$T \approx 2L/R$$

c) total current, i.e. area of the waveform or charge : $\int i\,dt = EC$

A set of waveform sketches were drawn for both the generators (see an example in Fig. 12), from which it was seen that the best compromise between peak and total current is reached when the circuit is critical, that is when it is :

$$\frac{R}{2}\sqrt{\frac{C}{L}} = 1$$

so that its response is intermediate between the exponential and the damped oscillatory one. In order to obtain a rise time of 5 μs, the generator a) could in principle be used with : C = 50 nF, E = 1 MV and R = 200Ω.

In practice the value of the resistance is not very critical; so that even when R is of the order of 100Ω the waveform is only slightly oscillatory but it maintains the main characteristics as wanted.

This can be seen in Fig. 9 where the computed value with R = 80Ω is compared with the measured one.

Since a resistance of 50Ω was added to the circuit, so that it is R = 80 ÷ 100 and the two waveforms are substantially similar, it can be inferred that the parameters were correctly estimated.

APPENDIX B

Since field measurements have been performed using shield wires of a rather short length (150 m) in a soil of rather low elec

tric resistivity ($\rho = 250\,\Omega\cdot m$), an extrapolation of the results must be made to the actual plants, where the shield wires can be assumed of indefinite length and the resistivity can be ten times higher or more.

The known solution for wires of indefinite length is the so called conductive energisation (ref. 1, § 5.9), which, for a given sinusoidal current I entering the soil at a distance k_o from a wire, gives the current I_o flowing into the wire as a function of the distance from the injection point.

In order to extrapolate the results, a representative frequency for the input current must be chosen. Both if the current is assumed as triangular, and a central frequency in the spectrum of a triangular waveform is chosen, and if the natural frequency of the circuit of Fig. 11 is assumed, a value of f_o = 30 KHz is obtained.

In order to estimate the reduction that a shield wire of indefinite length gives to the overvoltage on a nearby cable sheath, it is assumed that current in the soil is given by $I - I_o$, I_o being computed some meters away from the injection point, where it reaches its maximum value.

Now it is :

$$\frac{I_o}{I} = \frac{\Psi(\Gamma \ell, \Gamma k_o)}{K_o(\Gamma d'_g)}$$

where K_o is a modified Bessel function whereas function Ψ is given by :

$$\Psi(u,v) = \frac{1}{2}\left[e^{-u}\,\phi(u,v) - e^{u}\,\phi(-u,v)\right]$$

being :

$$\phi(u,v) = \int_{-u}^{\infty} \frac{e^{-\tau}\,d\tau}{(\tau^2 + v^2)^{1/2}}$$

(function ϕ is tabulated in ref. 1, Appendix A).

The arguments of the functions Ψ and K_o are :

a) the distance k_o from the injection point to the nearest point of the wire (see Fig. 13);

b) the wire equivalent diameter d'g, (ref. 1, § 3.6), which takes into account both the presence of one or two shield wires, and their laying depth; it results d'g = 51 mm for one shield wire and d'g = 129 mm for two shield wires;

c) the coordinate ℓ along the wire (see Fig. 13);

d) the parameter Γ given by :

$$\Gamma^2 = j\,\frac{\omega\mu}{2\rho}$$

being $\omega = 2\pi f_o$, μ the magnetic permettivity and ρ the resistivity of the soil.

The variation of I_o with ℓ is controlled by Γ and is represented in a typical case in Fig. 13. There is a short section near the injection point where current enters into the wire, so that current I_o in the wire increases in both directions.

Subsequently, for $\Gamma\ell \ll 1$ I_o reaches a maximum, and afterwards it flows from the wire into the soil, which is at a lower voltage; however I_o remains at a high level up to some units of $\Gamma\ell$.

In order to give a quantitative meaning to "long" and "short" wires, the characteristic length ℓ_o can be assumed for which it is :

$$|\Gamma \ell_o| = 1$$

in the sense that for a wire of length $\ell \ll \ell_o$ the current I_o cannot enter the wire, and it can be assumed as short, while if $\ell \gg \ell_o$ the current has already entered and left the wire as if it were infinitely long.

In the case of the experimental plant it is ℓ_o = 46 m so that the length of wire used can be assumed, if not infinitely long, at least rather long.

No tabulation of functions Ψ and ϕ has been made, since only orders of magnitude are of interest.

Assuming f_o = 30 KHz as a reference frequency, k_o = 5 m as a significant value, the relative current in soil due to one shield wire of indefinite length results :

$$\left|\frac{I - I_o}{I}\right| = \begin{cases} 0.83 & \text{for } \rho = 250\,\Omega\,m \\ 0.72 & \text{for } \rho = 2000\,\Omega\,m \end{cases}$$

Therefore the presence of one shield wire reduces the current in the earth to approx. 80% and 70% for low resistivity and high resistivity soils respectively, the comparison being made with the case in which no shield wire is present.

The amount of the reduction obviously increases with the increase of the soil resistivity, but it is not very important because a soil resistivity 8 times higher gives rise to a reduction of to current in the soil only of approx. 10%.

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2 K. Berger - E. Vogelsanger : "Messungen und Resultate der Blitzforschung der Jahre 1955 - 1963 auf dem Monte San Salvatore" Bull SEV, v. 56 (1965), p. 2 - 22.

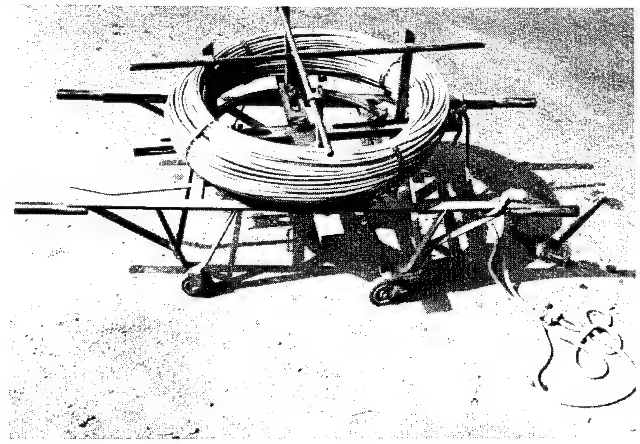

Fig. 1 shield steel rod arranged on the reel-winder

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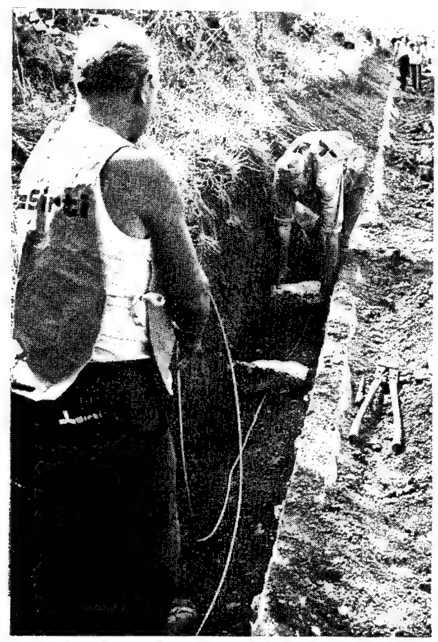

Fig. 2 laying the steel rod in the trench above the cable

Fig. 3 preparing the ends of the steel rod for jointing two adjacent lengths

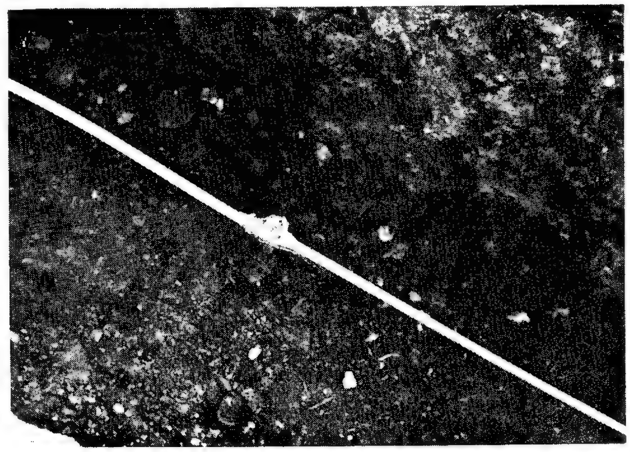

Fig. 5 welded joint

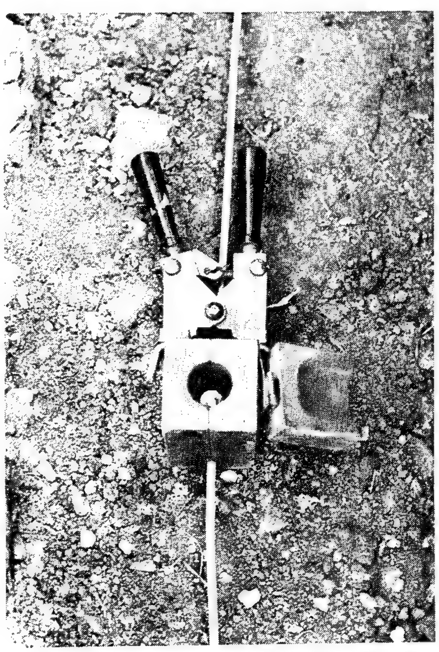

Fig. 4 arranging the two ends of the steel rod in the crucible for thermit welding

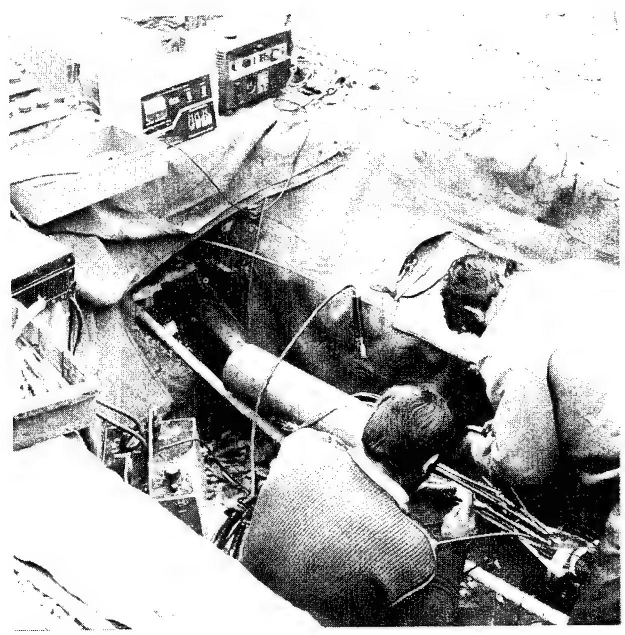

Fig. 6 jointing coaxial pairs. The steel rod can be seen above the joint

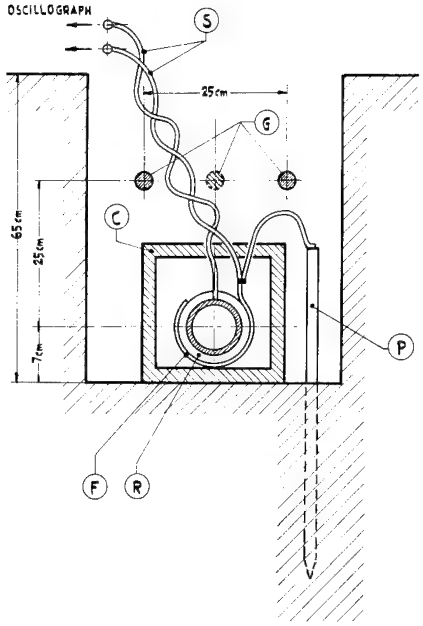

Fig. 7 layout of cable, shield wires and measuring probes

C = cement conduit

F = copper binder which connects outside of polyethylene sheath and nearby soil

P = earthing rod for binder F

G = shield wires (galvanized steel rods ∅ = 8 mm); measures have been made with no, one and two wires

S = measuring probe of the sheath overvoltage

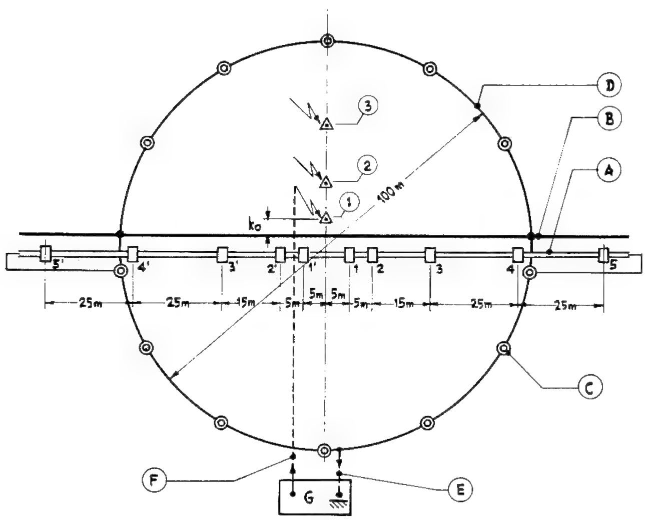

Fig. 8 general layout of the experimental plant

A = telephone cable sheath

B = shield wires (no rod, one or two galvanized steel rods)

C = earthing rods

D = connection of the earthing rods (insulated copper conductor 95 sq. mm. cross section)

E = connection between earthing rods and generator's earthing plate (insulated copper conductor, 95 sq. mm. cross section)

F = connection between generator's output and earthing rods (bare copper conductor 1.5 sq. mm. cross section)

1-1'-2-2'-3-3'-4-4'-5-5' show the position of the measuring probes

△ injection rods ① k_o = 5 m
② k_o = 10 m
③ k_o = 25 m

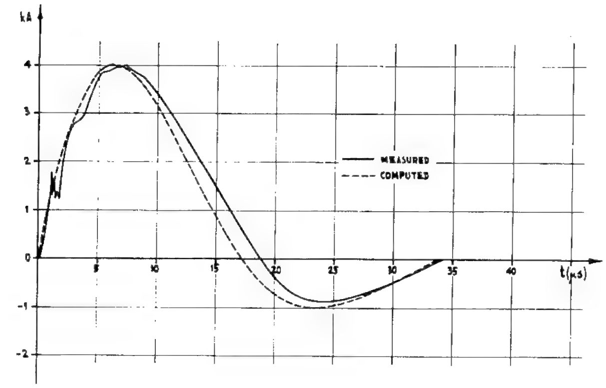

Fig. 9 injected current

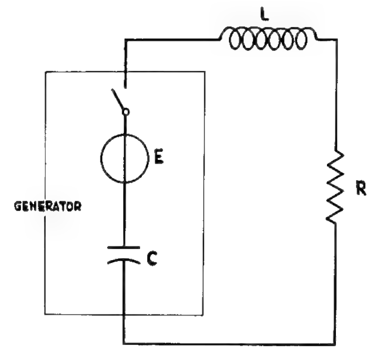

Fig. 11 equivalent circuit of the experi mental plant

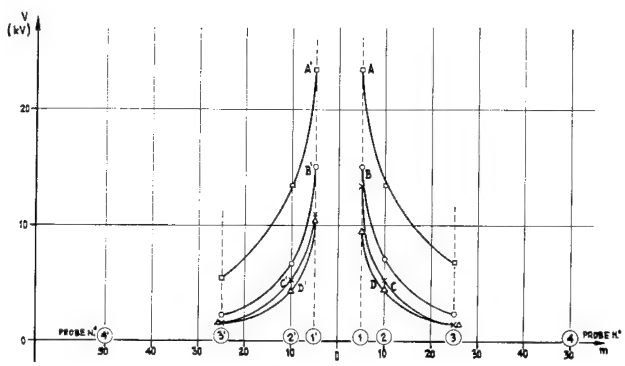

Fig. 10 peak voltages on the probes, I = 4 kA, k_o = 5 m

A A' without shield wires

B B' with one shield wire

C C' with two shield wires

D D' with two shield wires 8 months after the laying and backfilling operations

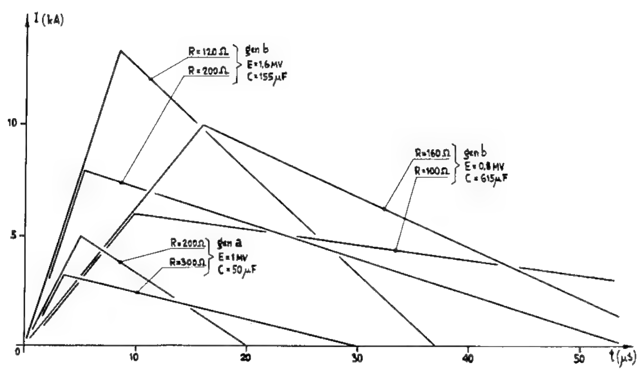

Fig. 12 schematized waveforms

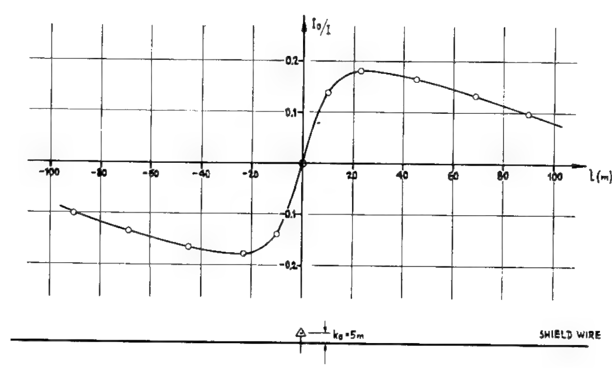

Fig. 13 current in the shield wire.

EMI/RFI SHIELDING OF CONNECTOR-TO-CABLE TERMINATIONS

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ABSTRACT

EMI/RFI SHIELDING OF CONNECTOR-TO-CABLE TERMINATIONS

Electromagnetic Compatibility of connector/cable terminations has become extermely important in recent years, and from all indications it will become more important in the future.

This paper will describe various methods of terminating connector to cable shields including descriptions of repairable and non-repairable systems and their respective advantages and disadvantages.

EMI/RFI SHIELDING OF CONNECTOR-TO-CABLE TERMINATIONS

Electromagnetic Compatibility of connector/cable terminations has become extremely important in recent years, and from all indications it will become more important in the future.

This paper will describe various methods of accomplishing this shielding, with special emphasis on those in general use, pointing out their respective advantages and disadvantages. A major element of connector-to-cable shielding is the cable shield termination, and consists of repairable and non-repairable systems, ranging from solder type ground rings, to conductive elastomers.

The problem confronting the design engineer is how to terminate his cable shielding to the connectors, obtaining a good mechanical joint and at the same time maintaining the EMI/RFI integrity of the system. We shall examine the terminating methods available, pointing out their advantages and disadvantages and for simplicity we shall discuss overall shielding, bearing in mind that all of the systems described can be terminated either overall or individual shielding or both.

1. Original Methods

Initially there were two basic methods used:

a. After the connector has been terminated the shielding would be flared up over the end of the connector and held in place by lacing cord or a piece of wire. (Fig. 1a)

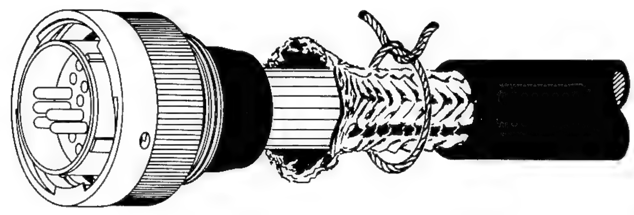


Fig. 1a

The advantages of this system is that it requires no special hardware or special tools and of course is inexpensive, but the disadvantages far outweigh the advantages because for effective shielding we must have electrical continuity between the shielding and the connector. This method can not guarantee this, also we have a poor mechanical joint which can come loose at the first movement of the cable.

b. This method consists of pigtailing the shielding and wrapping it around one of the connector clamp screws. (Fig. 1b)

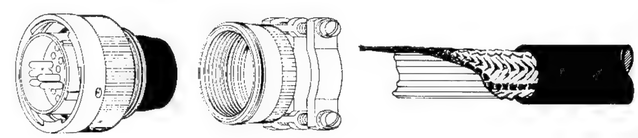


Fig. 1b

The advantages are exactly the same as in method (a), plus it is a good mechanical joint. The main disadvantage of this method is that we now have an unshielded portion of cable between the strain relief clamp and the connector which for effective shielding is unacceptable.

The two methods of EMI/RFI shield termination described are totally unsatisfactory for todays systems and I would recommend that designers avoid these systems.

2. Non-Repairable Terminations

There are two basic non-repairable methods used:

a. The first method is where we solder the shielding to the rear end of the terminated connector or to a special adapter. (Fig. 2a) The advantages gained through solder are: A good electrical joint, good shielding, and an average mechanical joint. The disadvantages, however, far outweigh the advantages. Special tools and techniques are required, plus high operator skills to ensure a good, smooth termination. Of course, there is the ever present danger of burning shielding and worse yet, burning insulation and causing major damage.

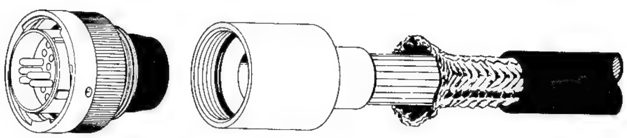


Fig. 2a

b. The second method in this category is crimping. (Fig. 2b) Here we pass a crimp ring over the shielding to a convenient distance from the end of the cable so as not to interfere with subsequent assembly steps. The connector then must be terminated. Following this step, the crimp adapter must be assembled to the connector and the shielding flared over the crimp area of the adapter. Next the crimp ring must be brought forward over the shielding to its crimping position. When this is accomplished a crimp tool must then be used to make the permanent joint.

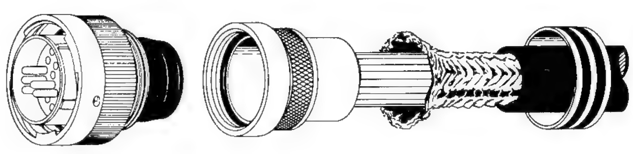


Fig. 2b

This method makes a very good electrical and mechanical termination and is inexpensive in large quantities. However, unless cable sizes are standard we could get either over crimping or under crimping. If we over crimp (too much squeeze) we can damage the inner conductors and dielectric. If we under crimp (not enough squeeze) we have a weak joint which may pull loose.

Also, this system requires a special crimp tool for each size shield to be terminated. These are two basic non-repairable methods of terminating shielding. Both can give excellent EMI/RFI shielding but require operator skills and special tooling and do not allow for any mistakes during the terminating. Both methods have their place but a designer should consider very carefully all the disadvantages before using either method.

3. Repairable Terminations

The last category of EMI/RFI Shielding of Connector-to-Cable Terminations is the Repairable Method:

a. The first method we will examine is the Grounding Ring. (Fig. 3a) Here we need a special adapter which is assembled to the terminated connector. Then the shielding is flared to 90^{o} and offered to the rear of the adapter. Then the Grounding Ring which has previously been installed over the shielding is slid forward and fastened to the rear of the adapter, trapping the shielding between the adapter and the ground ring. This makes an inexpensive termination but care must be taken to distribute the shielding evenly around the periphery of the adapter, otherwise only partial clamping will ensure causing intermittency and shielding failure.

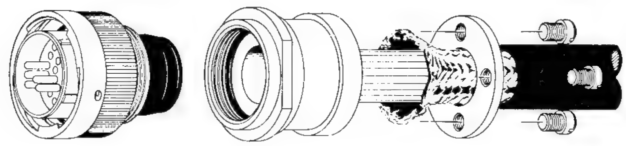


Fig. 3a

b. The second method in this category will be "Spring Fingers". (Fig. 3b) This form of termination is used where low cost is of importance as all we achieve is an electrical joint which accomplishes the desired shielding. Mechanically we achieve nothing and have to rely on a strain relief to hold the shield in place.

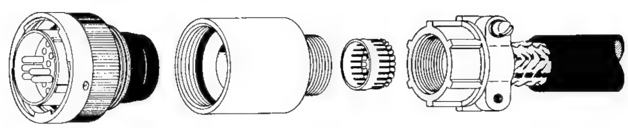


Fig. 3b

We need a special adapter with a ring made of beryllium cooper spring fingers soldered into the rear. The adapter is then installed onto the cable at a convenient distance from the end so as not to interfere with subsequent assembly steps. Then the connector is terminated and the adapters brought forward and assembled to the connector.

This automatically engages the spring fingers with the shielding giving continuity and EMI/RFI shielding.

The advantages in this method are as mentioned, low cost and the ability of the spring fingers to compensate for shield irregularities. The disadvantages are: No mechanical retention (other than spring pressure which is very light) and the fragile nature of the spring finger, which can be damaged easily.

c. The third method to examine is conductive elastomers. (Fig. 3c) These usually consist of copper balls 2-3 mils in diameter, which have been silver plated and used as a high volume filler for silicone or some other suitable elastomer. To terminate shielding by this method we mold a compression grommet from the conductive elastomer, and together with a special adapter we proceed as follows:

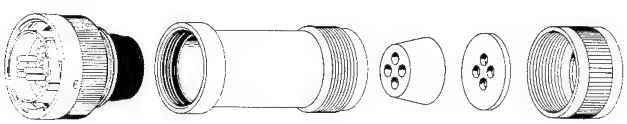


Fig. 3c

Pass the compression nut, friction washer, conductive grommet and adapter over the cable to a convenient distance from the end so as not to interfere with subsequent assembly steps. Then the connector is terminated and the adapter assembled to the connector. Next the grommet is brought forward ensuring it covers a portion of the shield. Last the friction washer and clamp nut are brought forward and torqued down until the grommet grips the shielding.

The advantages of this system are that we can terminate a large range of shielding, take care of any irregularities and if necessary, attain a moisture seal all with one component.

Disadvanatages are high cost and low grommet material tear strength plus the need to be protected from a salt atmosphere.

d. The fourth method makes use of a split collet. (Fig. 3d) Here the compression nut, collet and adapter must be passed over the shielding to a convenient distance from the end of the cable so as not to interfere with subsequent assembly. Then the connector must be terminated and the adapter assembled to the connector. The shielding is then flared over the knurled end of the adapter and the collet brought forward and positioned over the shielding. Finally, the compression nut is engaged and torqued to the reccommended value.

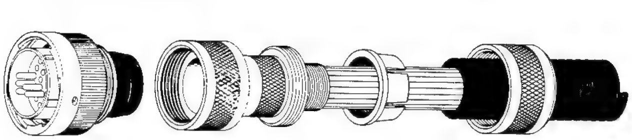


Fig. 3d

The advantages of this system are a good electrical and mechanical joint. The ability to compensate for large differences in shield diameters and very high retention. The disadvantages are: If torque values are exceeded there is a danger of cutting the shielding; also, the collet will only give a line contact on the shielding.

e. The fifth method in this category is the double cone method. (Fig. 3e) There are many variations of this method but we will examine just one. The compression nut, female cone, and adapter must be passed over the shielding to a convenient distance from the end of the cable so as not to interfere with any subsequent assembly. Then the connector must be terminated and the adapter assembled to the connector. The shielding is then flared over the integral male cone on the adapter and the female cone brought forward over the shield. Finally, the compression nut is assembled, squeezing the shielding between the two surfaces of the cones. The advantages of this system are excellent electrical and mechanical joint, high shield coverage, the ability to accommodate various shield thicknesses and low cost.

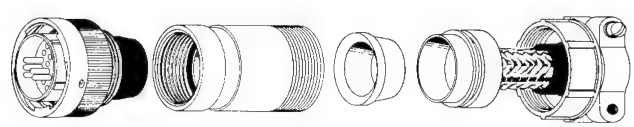


Fig. 3e

Disadvantages are mainly if angle of cone is too steep where shielding makes the transition from the cone, windows can be opened thus degrading the EMI/RFI integrity.

f. The sixth and last system is the Terminating and Grounding Ring. (Fig. 3f) This consists of an adapter with a castellated, threaded rear end and a clamp nut which has a captured beryllium copper spring and teflon friction washer. The adapter and compression nut can then be slid over the shielding to a convenient distance from the end of the cable. The connector is then terminated and the adapter assembled to the connector. The shielding is separated and fed into the castellated slots of the adapter. The clamp nut is brought forward picking up the members in the adapter slots and tightened down until all the shield is firmly clamped completing EMI/RFI termination. The advantages of this system are an excellent mechanical and electrical joint. The ability to terminate shields from zero to 3/16 inch thick plus being able to compensate for 1/32 inch

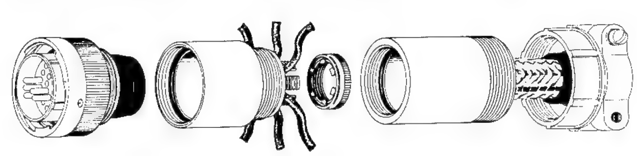


Fig. 3f

difference in shield thickness from slot to slot. Also, the ability of visual inspection to ensure correct termination.

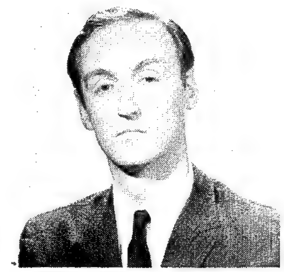
This, in conclusion, describes the various methods available to achieve a good EMI/RFI connector-to-shield termination. It must be envinronmental and can be obtained as separate components (without an adapter).

Also, overall shielding has been used as an example but each method applies equally well to individual shielding or a combination of both.

I would recommend that the design engineer use the termination methods described in the last category. Unlike the first and second categories he is always able to repair his system without having to replace expensive connectors and cabling.

BIOGRAPHY

Gerald G. Burge is Chief Engineer of Glenair, Inc., Glendale, California, directing the design activities for all types of connector accessories, special connectors and interconnection systems. Prior to joining Glenair in 1968, he was employed for 3-1/2 years by ITT Cannon Electric as a design engineer, and for the previous nine years as a design engineer with mechanical and electromechanical firms in England. He received a B.S. in Mechanical Engineering in 1956 from Paddington College, London, England.



MEASUREMENT OF THE DISSIPATION FACTOR OF POLYETHYLENE AT HIGH FREQUENCIES

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Abstract

The Hewlett-Packard 4342A Q-Meter and the General Radio Type 1690A Dielectric Sample Holder can be made the basis for apparatus capable of measuring dielectric dissipation factors of polymers to below 10^{-5} in magnitude and over a frequency range from below 100 KHz to at least 50 MHz. Modification of the sample holder to permit high precision susceptance variation measurements of Q and use of these measurements in conjunction with Q-Meter readings provides a method of measurement free of several uncertainties which arise in measurements based on Q-Meter readings alone. The measurements are repeatable to $\pm$ 2% and the method is validated by the Bell Laboratories Conductance Standard, to better than 1% at most frequencies. A correction is proposed for the effects of an air layer over portions of the area of samples of uneven thickness. Sample data for one measurement and results on three Phillips polymers over a range of frequencies are presented.

Introduction

The trends toward higher frequency transmission in coaxial communication cables using polyethylene as dielectric and toward higher voltages in power cables with solid polyethylene insulation have created needs for improved methods for accurate measurement of the very small dissipation factor of polyethylenes over a wide range of frequencies. As part of a general effort to gain a deeper understanding of the electrical properties of Phillips Marlex® polyolefin resins and to develop improved resins for wire and cable applications, we have developed a resonant circuit method for the measurement of very small dissipation factors in the frequency range from below 100 KHz to around 50 MHz. It is similar in principal to that described by Hartshorn and Ward[1] in 1936, and more recently, with improvements, by Barrie[2] and by Reddish, et al[3], and is based upon readily available apparatus of moderate cost. Its usefulness is, of course, not limited to measurements on polyethylene.

The method to be described grew out of work conducted with a Boonton 260A Q-Meter. A General Radio Dielectric Sample Holder was mounted rigidly on top of the 260A, with some mechanical modification and removal of the internal capacitor from the resonant circuit to increase sensitivity. Using coils constructed and shielded as will be described below and obtaining dissipation factors entirely from Q meter readings, this method gave good reproducibility in measurements of D as low as 10×10^{-6} and at frequencies to 50 MHz. When the Hewlett-Packard 4342A Q-Meter became available the method was adapted to it without internal modification and with considerable improvement of sensitivity and convenience.

The 4342A Q-Meter has far better oscillator isolation and amplitude and frequency stability than the 260A and lends itself readily to susceptance variation and frequency variation experiments. Certain measurement problems led us to a critical investigation of the method, using these techniques, and led finally to the method described in this paper, in which the relative decrease in circuit Q caused by a dielectric sample is obtained from Q-Meter readings but the absolute level of Q is obtained by susceptance variation.

Apparatus

Figure 1 shows photographs and Figure 2 a block diagram of the apparatus. It is assembled around a Hewlett-Packard 4342A Q-Meter with a 1/4 inch brass plate replacing the sheet metal top panel, grounded at the left hand shield ground. A General Radio Dielectric Sample Holder, Type 1690A, is mounted on a smaller brass plate having a hole cut out under the (unused) bottom access terminal, and this smaller plate is mounted on the base plate, with screws, in a position which places the left side access terminal of the sample holder one inch to the right of the center line of the Hi Coil terminal of the Q-Meter. The sample holder and its mounting plate are easily removeable. When it is put in place, the cap of the Hi-Cap terminal of the Q-Meter is removed and the caps of the Hi and Lo Coil terminals are replaced by hexagonal brass posts, one inch high, threaded 1/4-28 throughout their length. An aluminum coil shield box, 14 x 14 x 15 inches, with door in front, is screwed to the base plate in a position such that its right side almost touches the left side of the sample holder. The coils terminate in

flat copper straps with 9/32 inch holes through which they are bolted to the Hi and Lo Coil posts. A thin copper strap fits under the foot of the coil on the Hi Coil post and extends, through a hole in the shield box, to the side access terminal of the insulated plate of the sample holder.

The sample holder was modified by replacing the threaded shaft which forms the grounded member of the vernier capacitor by a brass shaft turned down to 1/8 inch diameter for 7/8 inch from its inward end. This change increases the resolution of the vernier capacitor from 0.5 pf per turn to 0.077 pf per turn. The vernier capacitor is used for peaking resonance and for measurement of Q by susceptance variation.

To obtain a Q Analog Output of high zero stability, the Q-Meter was modified by removing the Q-limit circuit board and replacing it with a small board which brings the output from the detector of the Q voltmeter to the back panel at the Q-limit output jack. To this jack is connected a unity gain operational amplifier with a ten-turn potentiometer gain control as its load resistor. The output of this amplifier goes to a switch having a straight-through position and a position with provision for applying an adjustable bucking voltage for zero suppression. Figure 3 is a circuit diagram of the operational amplifier and zero suppression circuits. The operational amplifier off-set null potentiometer is used to zero the detector output precisely and the gain control to set the output to 1.000 volts when the circuit Q meter reads 1000 (actually 997 with the amplifier connected, because of its loading effect). This output is read digitally on the two-volt range of a Simpson 460 Digital Volt-Ohm-Milliameter. Readings taken on the 200 mV range, with zero suppression, replace the ΔQ function of the Q-Meter.

A Heathkit Model SM-105 10 Hz-80 MHz Frequency Counter monitors the Q-Meter oscillator frequency at all times and was used in the frequency variation experiments to be mentioned.

In measurements of dissipation factor the control knobs of the internal measuring capacitors of the Q-Meter are set at their (off-scale) minimum positions, reducing the internal capacitance to about 18 pf. When measuring 30 mil disks slightly larger than the plates, the geometric capacitance of the sample holder is about 55 pf and the total capacitance of the Q-Meter and sample holder about 83 pf. Low frequency capacitance measurements were made at 10 KHz with a General Radio Type 1621 Capacitance Measuring Assembly.

High-Q coils were fabricated of one or more turns of copper tubing (1/8 inch to 3/4 inch diameter) or of bare wire. Descriptions of the coils most often used, together with their inductances and apparent distributed capacitances, $C_{d(app)}$, and typical working Q_o values, are given in Table I.

TABLE I

Coil Data

A. Physical:

No.	Conductor	No. Turns	Diam. (in.)	Length (in.)
1	No. 14 Copper	47	6-7/8	5-3/4
2	1/8" Copper Tube	25	5-1/4	6-1/4
3	3/16" Copper Tube	13	4	4
4	1/4" Copper Tube	3	4-1/4	1-1/4
5	3/4" Copper Tube	1	6-1/8	-

B. Electrical:

No.	L* (μH)	Apparent C_d(pf)	f_r** (MHz)	Q_o**
1	265	11.7	1.0	670
2	47	11.0	2.4	770
3	11.3	9.3	4.9	830
4	1.27	4.8	14.9	870
5	0.33	5.0	29	815

* L is slope of $1/\omega_r^2$ vs. C for coil mounted in shield box; C_d(apparent) is calculated from intercept using $1/\omega_r^2 = L\,[C + C_d(\text{apparent})]$

** Approximate f_r and Q_o for d_o = 13.0 mils, typical for 30 mil specimens

L and $C_{d(app)}$ were obtained from plots of $1/\omega_r^2$ vs. C in experiments in which the coil, mounted in the shielding box, was resonated at several values of the total capacitance as obtained from bridge measurements. Later work showed that only a fraction of $C_{d(app)}$ is true distributed capacitance, C_d, across the coil; the remainder, C_{LG}, is a capacitance from the Hi Coil terminal to ground electrically equivalent in total effect to the capacitances of the elements of area of the coil to the grounded base plate and shield box.

A Bell Laboratories Conductance Standard[4] was used to obtain correction factors in the work using Q-Meter indications alone and was later used to verify the performance of the revised method. This device consists of a very thoroughly shielded capacitance of 5.36 pf connected to the insulated plate of the sample holder, with provision for connection from it, to ground, of either a cylindrical high frequency resistor (1 to 300 ohm) or a shorting bar. The conductance standard is mounted on an aluminum plate which replaces the front door of the sample holder; a short banana plug, screwed into the standard, inserts in a banana jack fabricated to fit the threaded hole in the front of the insulated plate of the sample holder. The banana jack, the grounded mounting plate and housing, and the internal structure of the standard add about 8.5 pf from the insulated plate to ground, in addition to the 5.36 pf in series with the resistor or shorting bar.

When first received and in later checks all Q-Meter calibrations which could be checked with instruments at hand were found to be well within specifications. A downward drift of indicated Q occurs, however, for several hours after turn-on and the instrument is therefore left on continuously.

Sheets of polymer for dissipation factor measurement are compression-molded in a laboratory press with heated platens and provision for cooling at 15°C per minute with circulating water. Disks 2-1/8 inches in diameter are cut from these sheets and are inserted in the sample holder so that they extend beyond the two-inch plates about equally around the circumference. Most work has been done with relatively thin (30 mil) specimens in order to make the geometric capacitance affected by the sample the greater part of the total capacitance and to reduce the small uncertainty involved in neglecting fringe capacitance effects. Good agreement has been obtained with thicker samples. No difference has been found between dissipation factors obtained on 2-1/8 inch disks, on 2-3/8 inch disks and on 2 inch disks very carefully centered between the sample holder plates; the 2-1/8 inch disks are used for convenience.

Theory

The dissipation factor of a capacitor, represented by a parallel R-C equivalent circuit, is $G/\omega C$. G is an AC conductance in parallel with the capacitance which includes (1) the parallel conductance equivalent to the series resistance of current paths into the plates and (2) the conductance which arises from delayed polarization in the dielectric between the plates and in supporting insulators. The dissipation factor of a dielectric material is entirely of the second kind and is (in the absence of DC conductance) the ratio of the component of displacement current in phase with the electric field to the component which leads the field by $\pi/2$ radians.

The General Radio Dielectric Sample Holder is an adjustable parallel plate capacitor having a total capacitance, C_{SH}, consisting of (1) about 10 pf of stray capacitance, C_S, between the insulated plate and the housing, (2) the variable geometric capacitance, C_g, and (3) the small variable vernier capacitance, C_V. With air between the 2-inch diameter plates at separation d(mils), C_g is 706.5/d pf, plus a small fringe correction. With air between the plates the parallel AC conductance is G_{SH_o}, arising from the resistance in current paths plus delayed polarization in supporting insulators; the air between the plates contributes negligible conductance. When a dielectric sample is inserted which fills the space between the plates completely, an additional AC conductance ΔG_x is added, equal to $\omega C_g D_x$, where D_x is the dissipation factor of the dielectric. The dissipation factor of the sample holder with dielectric sample in place, at plate spacing d_1, is $D_{SH} = G_{SH_o}/\omega C_{SH} + \Delta G_x/\omega C_{SH}$; with air between the plates, at the smaller spacing d_o which produces the same C_g and C_{SH}, D_{SH} is $G_{SH_o}/\omega C_{SH}$. The ratio d_1/d_o is the dielectric constant of the dielectric. The dissipation factor of the dielectric is $\Delta G_x/\omega C_g$, where C_g is the capacitance affected by dissipation in the sample, neglecting fringe effects.

The resonant circuit in the apparatus described in Section II and diagrammed in Figure 2 is redrawn in Figure 4 as a detailed equivalent circuit considered to be valid to beyond 50 MHz and, in condensed form, in terms of frequency-dependent lumped parameters.

In addition to the components of C_{SH} mentioned, the total capacitance (C_e in Figure 4) in series with the inductance (L_e) and forming a series resonant circuit across the secondary of the signal injection transformer, includes C_m, the minimum internal capacitance of the Q-meter (about 18 pf) and C_{LG}, a capacitance between the Hi Coil terminal and ground which is equivalent in total effect to the capacitances to the grounded base plate and shield box of the elements of area of the inductor. That $C_{d(apparent)}$ has C_{LG} as its principal component was discovered, and then proved, in experiments which compared indicated Q values (Q_{ind}) read from the Q-Meter with the results of susceptance variation and frequency variation experiments, including artificially increasing C_d by connecting small capacitors across the coil terminals. At the higher frequencies the small inductances l_m, of the Hi Coil post itself and the structure of the Q-Meter capacitor, and l_{SH}, of the strap from the Hi-Coil post to the insulated plate and of the sample holder structure, make the effective values of C_m and C_{SH} and their associated conductances frequency-dependent. For the total effective capacitance, effective conductance and effective dissipation factor in series with the inductor we have

$$C_e = C_{LG} + C_m/(1-\omega^2 l_m C_m) + C_{SH}/(1-\omega^2 l_{SH} C_{SH}) \quad (1)$$

$$G_e = G_m/(1-\omega^2 l_m C_m)^2 + G_{SH}/(1-\omega^2 l_{SH} C_{SH})^2 \quad (2)$$

$$D_{C,e} = G_e/\omega C_e \quad (3)$$

The effective inductance of the inductor is frequency-dependent at all frequencies because of the effect of the parallel distributed capacitance. For the inductor we have

$$L_e = L/(1-\omega^2 L C_d) \quad (4)$$

$$R_e = R/(1-\omega^2 L C_d)^2 \quad (5)$$

$$Q_{L,e} = \omega L_e/R_e \quad (6)$$

The admittance of the series resonant circuit across the secondary of the signal injection transformer of the Q-Meter is

$$Y_{ckt} = 1/(Z_L + Z_C)$$

The small constant amplitude voltage, V_1, developed by the Q-Meter oscillator across this secondary, causes a current $i = Y_{ckt}V_1$ to flow through the resonant circuit and a voltage $V_2 = Z_c i$ to appear across the resonating capacitance. The ratio V_1/V_2 is

$$V_1/V_2 = (i/Y_{ckt})/iZ_c = 1 + Y_c Z_L$$

$$= 1 + (j\omega C_e + G_e)(j\omega L_e + R_e) \quad (7)$$

Expanding and multiplying by the complex conjugate yields

$$(V_1/V_2)^2 = (1 - \omega^2 L_e C_e + R_e G_e)^2 + (\omega C_e R_e + \omega L_e G_e)^2 \quad (8)$$

In our work the Q of the inductor is typically greater than 500 and the dissipation factor of the total capacitance less than .001. The difference between the capacitance at current resonance ($C_e = 1/\omega^2 L_e$) and that at voltage resonance ($C_{e,r} = \frac{1}{\omega^2 L_e(1 + 1/Q_{L,e}^2)}$) is of the order of parts per million and we approximate $C_{e,r}$ by $1/\omega^2 L_e$. $R_e G_e$ is equal to $\omega^2 L_e C_e \cdot \frac{D_{C,e}}{Q_{L,e}}$ and is negligible. With these simplifying assumptions eq. (8) becomes

$$(V_1/V_2)^2 = (1 - \omega^2 L_e C_e) + (\omega C_e R_e + \omega L_e G_e)^2 \quad (9)$$

and at resonance

$$(V_{1,rms}/V_{2,rms})_{res} = \omega C_e R_e + \omega L_e G_e$$

$$= \frac{R_e}{\omega L_e} + \frac{G_e}{\omega C_e}$$

$$= 1/Q_{L,e} + D_{C,e}$$

$$= 1/Q_{ckt} \quad (10)$$

If we describe the sample holder with dielectric sample at plate separation d_1 as condition 1 and with air at separation d_o and equal capacitance, at the same resonant frequency, as condition zero, we have

$$1/Q_1 = 1/Q_{L,e} + G_{e_o}/\omega C_e + \Delta G_e/\omega C_e$$

$$1/Q_o = 1/Q_{L,e} + G_{e_o}/\omega C_e$$

whence $$\Delta G_e = \omega C_e (1/Q_1 - 1/Q_o) = \omega C_e \frac{\Delta Q}{Q_1 Q_o} \quad (11)$$

ΔG_e is the increment of effective conductance caused by the increment ΔG_x added by the polymer to the conductance of the sample holder. From equation (2), which relates G_e to G_{SH}, we obtain

$$\Delta G_x = (1 - \omega^2 l_{SH} C_{SH})^2 \Delta G_e \quad (12)$$

The dissipation factor of the dielectric, $D_x = \Delta G_x/\omega C_g$, is then

$$D_x = (1 - \omega^2 l_{SH} C_{SH})^2 (C_e/C_g)(\Delta Q/Q_1 Q_o) \quad (13)$$

D_x is obtained from measurements of Q_1 and Q_o.

The Q-Meter measures Q directly by measuring $V_{2_{rms}}$ at constant V_1; Q_{ind} will be equal to Q_{ckt} if V_1 has exactly its design value and if the gain, A, of the Q-voltmeter circuit has also its design value. If, however, as a result of thermal drift or imperfect circuit adjustments, $V_1 = mV_1$ (design) and $A = nA$ (design), Q_{ind} will be mn Q_{ckt} and the ratio $\Delta Q/Q_1 Q_o$ will be mn $\Delta Q_{ind}/Q_{1ind}Q_{oind}$. For a D measurement from Q-Meter readings alone eq. (13) becomes

$$D_x = (1 - \omega^2 l_{SH} C_{SH})^2 (C_e/C_g)\ mn \left(\frac{\Delta Q_{ind}}{Q_{1ind} Q_{o,ind}}\right) \quad (13a)$$

Use of eq. (13a) to obtain D_x involves three factors which are difficult to determine and likely sources of error: (1) $(1 - \omega^2 l_{SH} C_{SH})^2$, at high frequencies, which requires that l_{SH} be measured, (2) C_e, which includes the difficultly measured component C_{LG} and is also frequency-dependent at high frequencies, and (3) the Q-Meter error factor mn. We next show that if $\Delta Q/Q_1$ is determined from Q_{ind} readings (which requires only that mn be a true proportionality constant at each frequency) and $1/Q_o$ is determined by susceptance variation, all three of the troublesome factors in eq. (13) cancel.

If the resonant circuit with air between the plates (condition zero) is detuned, at constant frequency, from Q_{oind} to $Q_{ind} = 0.707\ Q_{oind}$, by variation of the small vernier capacitance by $\pm\ \delta C_V$ (the resonance curve is symmetrical), we note that $(V_1/V_2)^2 = 2(V_1/V_2)^2_{res}$ and combine eq. (9) and eq. (10) to obtain

$$(1 - \omega^2 L_e C_e)^2 + (\omega C_e R_e + \omega L_e G_e)^2 = 2/Q_{ckt}^2 \quad (14)$$

Writing for C_e off resonance $C_e = C_{e,r} \pm \delta C_e = C_{e,r}(1 \pm \gamma)$, substituting in eq. (14), expanding, and using $\omega^2 L_e C_{e,r} = 1$ and $(\omega C_{e,r} R_e + \omega L_e G_e)^2 = 1/Q_{ckt}^2$, we obtain

$$\gamma^2 = (\delta C_e/C_{e,r})^2 = 1/Q_{ckt}^2 + \text{negligible small terms} \quad (15)$$

or, writing $\Delta C_e = 2\,\delta C_e$,

$$\Delta C_e/2C_{e,r} = 1/Q_o \quad (16)$$

where ΔC_e is the width of the resonance curve between half-power points. To relate ΔC_e to the experimental quantity $\Delta C_V (= \Delta C_{SH})$ we may, because ΔC_V is small, write

$$\Delta C_e = \frac{\partial C_e}{\partial C_{SH}} \Delta C_V$$

$$= \frac{\partial}{\partial C_{SH}} \left[C_{LG} + C_{m,e} + \frac{C_{SH}}{1 - \omega^2 l_{SH} C_{SH}}\right] \Delta C_V$$

$$= \Delta C_V / (1 - \omega^2 l_{SH} C_{SH})^2 \quad (17)$$

whence, writing simply C_e for $C_{e,r}$,

$$\frac{1}{Q_o} = \frac{\Delta C_V}{2C_e(1 - \omega^2 l_{SH} C_{SH})^2} \quad (18)$$

If we now rewrite equation (13) in terms of Q_{ind} readings for $\Delta Q/Q_1$ but substitute for $1/Q_o$ its value obtained by susceptance variation, we have, after simplification,

$$D_x = \frac{\Delta Q_{ind}\,\Delta C_v}{2\,C_g\,Q_{1,ind}} \tag{19}$$

as the final working equation. All three of the troublesome factors in eq. (13a) have cancelled.

Verification of the Susceptance Variation Method Using the Conductance Standard

When the conductance standard is attached to the sample holder C_{SH} is increased by about 8.5 pf of added stray capacitance plus 5.36 pf (C_{std}) in series with either a standard resistor or a shorting bar. R_{std} in series with C_{std} adds to G_{SH_o} an increment of effective conductance (the parallel conductance equivalent to R_{std} in series) given by $\Delta G_{std} = \omega^2 C_{std}^2 R_{std}$. At frequencies at which the effect of the inductance of the standard is negligible, C_{std} and ΔG_{std} will add to C_{SH} and G_{SH} without frequency correction and ΔG_{std} can be measured experimentally by a procedure similar to that used for a dielectric sample, with Q_1 measured with the resistor in place and Q_o with the shorting bar in place. From equation (11), (12) and (18) we have

$$\Delta G_{std} = \frac{\omega\,\Delta Q_{ind}\,\Delta C_v}{2\,Q_{1,ind}} \tag{20}$$

Forming the ratio of the theoretical and experimental expressions for ΔG_{std} yields

$$\rho = \frac{\Delta G_{std}(theory)}{\Delta G_{std}(expt)} = \frac{2\omega\,C_{std}^2\,R_{std}\,Q_{1,ind}}{\Delta Q_{ind}\,\Delta C_v} \tag{21}$$

Table II exhibits this ratio, which should of course be unity, determined over a wide range of frequencies and resonating capacitances.

TABLE II

Conductance Standard Data

Coil	C_m+C_{SH} (pf)	f_r (MHz)	$Q_{o\,ind}$	R_{std} (ohms)	ρ*
1	113.3	.870	628	59.72	0.997
	82.8**	1.000	670	59.72	0.993
	62.9	1.128	700	59.72	1.005
2	113.3	2.091	749	9.566	1.002
	82.8**	2.411	768	9.566	1.002
	62.9	2.730	811	9.566	1.008
3	113.3	4.240	804	3.004	1.005
	82.8**	4.896	827	3.004	1.010
	62.9	5.552	840	3.004	1.012
4	113.3	12.88	819	1.004	1.007
	82.8**	14.94	869	1.004	1.007
	62.9	17.03	935	1.004	0.998
5	113.3	24.94	731	1.004	0.997
	82.8**	29.10	816	1.004	1.000
	62.9	33.14	903	1.004	0.986

* $\rho = 2\omega C_{std}^2 R_{std} Q_{1ind}/\Delta Q_{ind}\Delta C$

** Corresponds to d_o = 13.0 mils with Conductance Standard removed, typical of d_o for 30 mil samples

At frequencies so high that the inductance of the standard must be taken into account the theoretical effective value of ΔG_{std} as it adds to G_{SH_o} becomes

$$\Delta G_{std}(theory) = \frac{\omega^2 C_{std}^2 R_{std}}{(1-\omega^2 \ell_{std} C_{std})^2} \tag{22}$$

while the experimental expression, a measure of the effective increment added to G_{SH_o} by R_{std}, remains unchanged. The ratio ρ calculated without the correction term in brackets in the denominator of eq. (22) should, therefore, fall below unity at the highest frequencies.

Effects of Uneven Sample Thickness

The work so far has assumed that the dielectric sample fills the space between the sample holder plates. In practice it is impossible to mold samples of precisely uniform thickness and an air layer will exist between the sample and one or the other plate over a part of the sample area. This air layer causes the apparent dielectric constant of the sample, d_1/d_o, always to be somewhat smaller than the true dielectric constant measured by the liquid displacement technique or calculated from the density (the true dielectric constant is independent of frequency over the entire range of interest, to at least the third decimal place).

To investigate the effect of thickness non-uniformity upon the measured dissipation factor, calculations were made for two models, assuming sample holder plates parallel at separation d_1 in both cases. In Model A the polymer sample is of uniform thickness d_p and the air layer of uniform thickness $d_a = d_1 - d_p$. In Model B half the area of the sample has thickness d_1 and the other half uniform smaller thickness d_p. For Model A the effective capacitance and dissipation factor of the polymer dielectric and air dielectric capacitances in series, and thus the effective values which would be obtained for the sample by measurement, are

$$K_e = \frac{d_1 K_{pol}}{(K_{pol}-1)d_a + d_1} = \frac{d_1}{d_o} \tag{23}$$

$$D_e = \frac{(K_e - 1)}{(K_{pol} - 1)} D_{pol} \tag{24}$$

Model B is a case of two capacitors of equal plate area of the type of A, in parallel, for one of which $d_p = d_1$ and $d_a = 0$; K_e and D_e for this model are

$$K_e = \frac{1}{2}\left(K_{pol} + K_e(d_a)\right) = \frac{d_1}{d_o} \tag{25}$$

$$D_e = \left[\frac{K_{pol}}{K_{pol} + K_e(d_a)} + \frac{K_e(d_a)\,[K_e(d_a) - 1]}{[K_{pol} + K_e(d_a)](K_{pol} - 1)}\right] D_{pol} \tag{26}$$

where $K_e(d_a)$ is the effective dielectric constant of the half of the plates over which an air gap exists. These two models should bracket the majority of actual cases of uneven sample thickness. In Table III, below, are tabulated D_e/D_{pol} calculated for the two models for values of K_e/K_{pol} down to 0.90, with K_{pol} assumed to be 2.300.

TABLE III

Correction Factors For Uneven Sample Thickness

$K_{pol} = 2.300$

	D_e/D_{pol}	
K_e/K_{pol}	Model A	Model B
1.00	1.00	1.00
0.99	0.982	0.982
0.98	0.965	0.965
0.97	0.947	0.949
0.96	0.929	0.932
0.95	0.912	0.916
0.93	0.876	0.886
0.90	0.823	0.843

The calculations in Table III show (1) that the effect of an air gap in reducing D_e below D_{pol} is greater than its effect upon K and (2) that the two extreme models agree to better than 0.5% down to $K_e/K_{pol} = 0.95$, or $K_e = 2.185$ for $K_{pol} = 2.300$. In routine work for internal purposes we ordinarily achieve $K_e/K_{pol} > 0.98$ and apply no correction, but the calculations indicate that a correction is necessary in work aiming at the highest accuracy.

Measurement Procedure

In the description below "read Q" means read the DVM on the two-volt scale with switch S (Figure 2) set in the straight through position, and "read ΔQ" means read the 200-mv scale of the DVM after setting S to zero suppression and introducing an arbitrary bucking voltage to bring the output within range. The vernier capacitor, C_V, is set at 3.5 on its scale at the start. The steps are:

1. Install a working coil.
2. Insert a sample and close the sample holder plates.
3. Tune the oscillator to f_r and record f_r.
4. Determine the plate separation, d_1, by backing off the main micrometer until the indicated Q just begins to fall, and record d_1. The plates are then closed.
5. Read and record ΔQ_1, peaking with C_V.
6. Read and record Q_1.
7. Remove the sample, close the plates to restore resonance and record d_o.
8. Read and record ΔQ_o, peaking with C_V, without changing the zero suppression voltage.
9. Read and record Q_o.
10. Repeat steps 2-9 at least three and preferably five times.
11. With the sample removed and the DVM indicating Q_o, detune to 0.707 Q_o by turning C_V inward. Record C_1'.
12. Turn C_V outward through Q_o to 0.707 Q_o and record C_2'.
13. Repeat steps 11 and 12 twice, or more if there is disagreement.
14. Calculations:
    a. Calculate K_e as d_1/d_o
    b. Calculate C_x as $706.5/d_o$ pf
    c. Calculate ΔC as 0.154 $(C_2' - C_1')$ pf, averaging $C_2' - C_1'$.
    d. Calculate ΔQ as the average value of $\Delta Q_1 - \Delta Q_o$ (Q_1 and Q_o will normally not change; if they do, average Q_1)
    e. Calculate D_e as $\Delta Q \; \Delta C/2Q_1C_x$
    f. If K_{pol} is known and highest accuracy is required, calculate D_{pol} as $\left[(K_{pol}-1)/(K_e-1)\right] D_e$.

In work with the conductance standard the procedure is the same except that $d_1 = d_o$, set to the desired frequency, and alternate insertion of the standard resistor and the shorting bar replace insertion and removal of the sample.

An attractive variation* of the procedure involves setting d_1 slightly greater than the sample thickness in step 2, omitting step 4, and carrying out calculation step 14 f., thereby avoiding the error arising from uneven sample thickness. K_{pol} must of course be known accurately.

Results

A sample data sheet for a dissipation factor measurement at 4.84 MHz is reproduced as Table IV.

*Suggested by G. E. Johnson of Bell Laboratories.

TABLE IV

Measurement of D_{pol}

Sample Data

Polymer: A, Density: 0.962, K_{pol}: 2.361
d_1: 29.4 mils, d_o: 12.7 mils
Coil: No. 3, f_r: 4.838 MHz

1. Q_o, Q_1 and ΔQ Data:

ΔQ_1	Q_1	ΔQ_o	Q_o	ΔQ $(= \Delta Q_o - \Delta Q_1)$
2.0	847	9.0	854	7.0
2.0	847	9.0	854	7.0
1.8	847	8.8	854	7.0
1.5	847	8.5	854	7.0
1.4	847	8.4	854	7.0

2. Susceptance Variation Data:

C' for $Q_{ind} = .707\ Q_o = 604$

Expt.	C_2'	C_1'	$\Delta C'$
1	4.139	2.749	1.390
2	4.139	2.749	1.390
3	4.140	2.750	1.390

3. Calculations:

$$K_e = d_1/d_o = 2.315$$
$$C_g = 706.5/d_o = 55.63 \text{ pf}$$
$$C = 0.154\Delta C' = .2141 \text{ pf}$$
$$D_e = \frac{\Delta Q\ \Delta C}{2C_g\ Q_1} = 15.9 \times 10^{-6}$$
$$D_{pol} = \left(\frac{K_{pol}-1}{K_e-1}\right) D_e = 16.5 \times 10^{-6}$$

The symbols in this table will be clear from the description of the procedure, but a few remarks are necessary. The value of D is calculated to three significant figures but we do not suggest that the third figure is certain; in practice we find measurements repeatable to about $\pm$ 2%. We calculate C_x as C_g $(= 706.5/d_o)$ without fringe correction; at $d_o = 13.0$ mils the fringe correction is about + 0.3 pf and would increase C_x from 55.63 pf to about 55.9, reducing D_e slightly (about 0.5%). The susceptance variation results are reduced in accuracy by the fact that Q_{ind} (Q_o and 0.707 Q_o) can be read only to a full unit; one more digit of DVM read-out would enable us to take full advantage of the precision to which C' can be read. K_e is calculated to more significant figures than the precision of reading d_1 and d_o justifies. K_{pol} is calculated from the density as $K = 2.276 + 2.01 (d-0.9200)$[5]; experimental measurements by the liquid displacement method have given results very close to those calculated from this equation. In theory D_e should be multiplied by the factor ρ (Table II) obtained with the conductance standard but the correction is so small we neglect it.

In the course of studies on many polymers we have often encountered samples so uneven that K_e/K is 0.95 or less and have made a policy of rejecting such samples and molding new test sheets. If the amount of polymer available is so small as to preclude doing so the simple correction for uneven thickness can be used with acceptable error.

Measurements are ordinarily made at ambient temperature in an air-conditioned laboratory, ranging from about 70°F to 77°F (21° to 25°C); 73°-75°F is usual. The calibration error factor (mn) of the Q-Meter is somewhat temperature sensitive. It is an advantage of the method using susceptance variation that the results are independent of mn and will not be affected by the larger changes to be expected if the temperature of the sample holder is varied by external means and the internal temperature of the Q-Meter is perturbed by heat conduction.

As examples of results obtained by this method over a range of frequencies, the dissipation factors of three experimental Phillips process polymers, coded A, B, and C, are plotted vs. log frequency in Figure 5. The polymers represented were molded directly from as-polymerized "fluff" with inclusion of 0.05% BHT (2,6 Di-tert-butyl-p-cresol), an antioxidant which contributes negligibly to dissipation factor. Experimental polymers which had not been subjected to the polymer stabilization and pelletizing operation were chosen as examples in order to avoid perturbation of the results by antioxidants and possible small changes during the pelletizing extrusion. It will be observed, in Figure 5, that the plots of D vs. log frequency are smooth curves, rising with increasing frequency, to which the individual data points fit quite closely. It is instructive to compare the shapes of these curves with those published by Barrie, Buckingham and Reddish[6] in 1966, for two high pressure process polyethylenes over a much wider range of frequency. The shapes are generally similar.

The well known increase of dielectric loss of polyethylene with oxidation or contamination has led some to propose that an entirely pure polyethylene should be without loss. Barrie et al[6] argue against this assumption and we concur. In loss measurements on many polymers closely similar in type we have found D to vary in a systematic way when certain other properties varied and to be quite closely reproducible for different preparations of polymers for which other measureable properties were closely reproduced. This observation argues against trace contamination or oxidation as the source of loss; contamination would be expected to vary in a more random fashion.

Acknowledgements

Sincere thanks are due to Dr. Gordon Link and Mr. G. E. Johnson, of Bell Laboratories (Murray Hill), for the theory and use of the conductance standard and for other helpful discussions and suggestions. Mr. V. L. Moore, of Phillips, designed the operational amplifier circuit used for drift-free digital read-out of Q and Mr. L. P. Thomas carried out most of the laboratory measurements. Dr. J. Paul Hogan, Mr.

D. D. Norwood and many other colleagues have made invaluable contributions to the studies of which the present work is a part.

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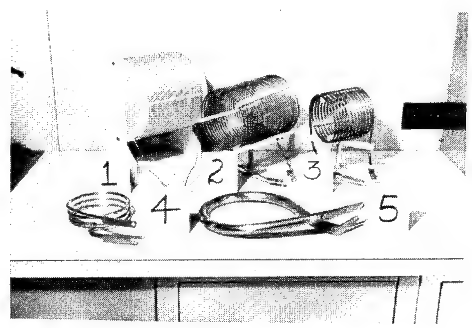
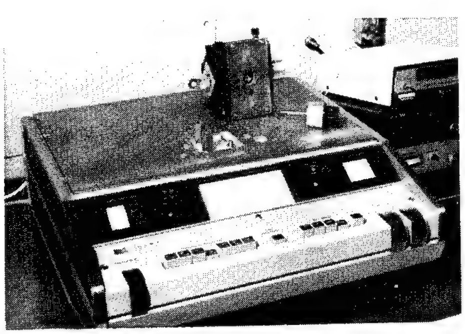
M. T. O'Shaughnessy received the Ph.D. in Physical Chemistry from the University of Illinois. He has been employed in film and fiber research at duPont, in fiber research management at American Viscose Corporation, and in defense-related research management with the National Defense Research Committee in World War II and at Aerospace Corporation, Los Angeles, in 1961-66. From 1946 to 1954 he was a member of the chemistry faculty of The Polytechnic Institute of Brooklyn. He joined Phillips in 1966 as a branch manager of fiber physics and since 1969 has been engaged, as Senior Research Associate, in fundamental studies in polymer physics.

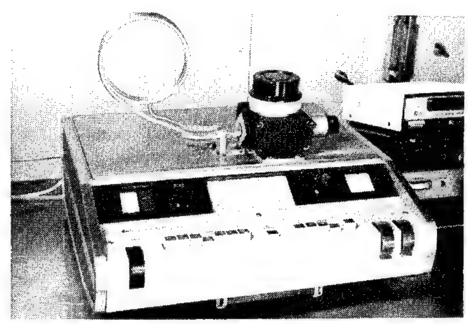
A. Assembled Apparatus



B. Coils



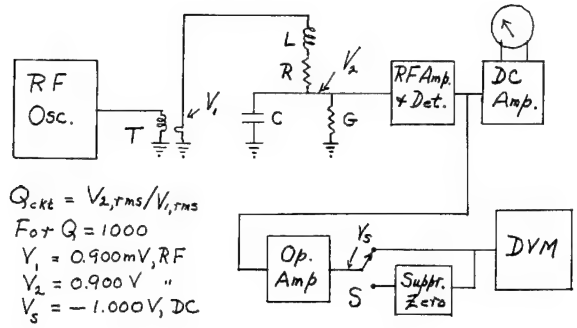
C. Sample Holder Mounting



D. Detail of Coil Mounting

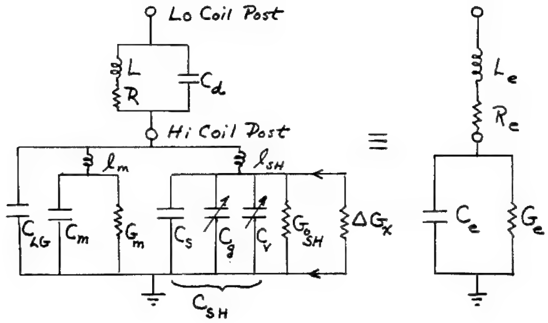
VIEWS OF APPARATUS

Figure 1



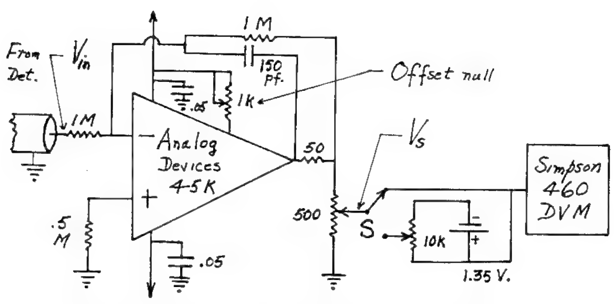
Block Diagram

Figure 2



Equivalent Circuit

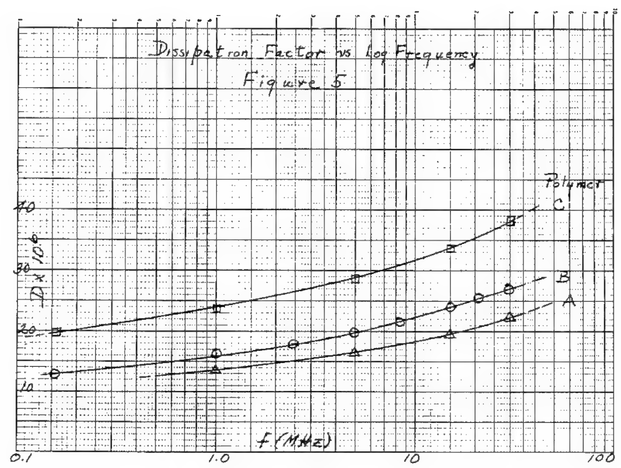
Figure 4



For Q = 1000: $V_{in} \simeq 1.59$ V., $V_s = -1.000$ V.

Operational Amplifier Circuit

Figure 3



STABILIZATION PROBLEMS WITH LOW DENSITY POLYETHYLENE INSULATIONS

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Abstract

Examination of samples from the field confirms that the premature brittle failure of low density polyethylene telephone cable insulations in pedestal-type terminations in the warmer areas of the country is due to copper-catalyzed oxidative degradation of the polymer. This degradation evidently results from the interaction of a number of variables, one of the more important being early depletion of the antioxidant. Time, temperature, insulation wall-thickness, pigmentation, and migration of the stabilizer are all recognized as potential contributors to the failures.

Introduction

At the 20th International Wire and Cable Symposium, Pusey, Chen, and Roberts[1] presented a very competent analysis of the premature field failure of some low density polyethylene telephone cable insulations, substantiating earlier conclusions of Hawkins, Chan, and Link based on laboratory data and calculations[2]. This paper deals with similar field failures in Bell System plant, the first instances of which were reported in Tucson, Arizona in July 1970. These reports led to an extensive field survey under direction of the Quality Assurance Center of Bell Laboratories, analysis of the results of which constitutes a substantial portion of this report. The significance of the information developed in the course of this study is far-reaching. It affects not only the communications cables discussed and analyzed here, but all uses of polyethylene where long-lived protection against oxidative degradation is important.

Field Survey

The field survey involved some 1100 terminals in 13 cities, shown on the map of Figure 1. Failures were found in 287 of these. In addition, failures have been reported from five locations not included in the survey; hence a total of 18 failure sites are shown in Figure 1. The failures encountered were all in pedestal-type terminations associated with buried plant, typical examples of which are shown in Figures 2 and 3. No failures have as yet been found in aerial splice cases, nor in those portions of any cable where the sheath had not been removed to provide free access to the individual pairs. Typical failed insulation is shown in detail in Figure 4.

The results of the survey can be analyzed in a number of different ways. It is obvious, for example, that the failure locations are all in the southern tier of states, below about the 37th parallel of north latitude. This immediately suggests a temperature dependence, but direct correlation with available National Weather Service data proves difficult to demonstrate. A convenient approach, suggested by W. L. French, succeeds in relating cable age at time of failure to a composite temperature factor: average maximum temperature plus number of days over 90°F. This provides a narrow envelope embracing all the failure sites for which temperature data are available, as shown in Figure 5.

More directly related temperature measurements are being obtained on a continuous basis in specially equipped terminals at several sites by D. Edelson of Bell Laboratories. A graphical summary of his data for temperature extremes in a typical pedestal and in a nearby aerial splice case in Phoenix for the month of August 1971 is shown in Figure 6. It is readily apparent that the aerial terminal remains substantially cooler than the pedestal most of the time. It is also apparent that the latter normally remains well below the maximum (approximately 70°C) anticipated on the basis of earlier measurements by ourselves and others[3-5]. Edelson's data are not complete, but they already indicate a 10 to 15°C differential between aerial cases and pedestals, and a maximum of about 60°C for the latter on

rare occasions. (The maximum shown in Figure 6 is only about 52°C). This differential between aerial and ground plant helps to rationalize the absence of failures thus far in Bell System aerial terminals, but the temperatures being found for the pedestals are discouraging in that they indicate that failures have occurred at rather lower temperatures than had been thought.

Another obvious basis for analysis of the failures is by year of installation. This has been done in Figure 7. Surprisingly, there appears to be no straightforward relationship between age and failure rate. More surprising yet, the oldest cables examined have shown no failures. It seems clear from the lack of pattern here that the failure process must result from a combination of variables, with time not necessarily the most important.

Attempts to correlate failures with gauge size of the conductors involved reveals that cracks are found in the 24 and 26 gauge insulations about twice as frequently as in the larger 19 and 22 gauges where the wall thickness is greater.

Figure 8 shows the distribution of failures by insulation color. Since equal numbers of conductors of the various colors appear in these cables, a purely random distribution should produce equal numbers of failures in each color. This is clearly not the case. In agreement with the experience of Pusey, et. al., the failure rate for the white insulations is found to be abnormally high, and so is that for the red, which contains only half the amount of titanium present in the white or in most of the other colors. No explanation for this can be suggested at present.

The most significant feature of these data is the fact that, to date, not one failure has been found in a black insulation. There can be several possible reasons for this. Carbon black, particularly the channel-type involved here, is a weak but persistent antioxidant for polyethylene in the solid state[6]. Also, the black insulation is the only one which does not contain titanium dioxide. Lastly, it is possible that even the small amount of carbon black used (0.4%) may help to retain the antioxidant. Whatever the reason, it is quite evident that the black insulations are more effectively protected against degradation than any of the others.

Characterization of Failures

The physical appearance of these failures automatically suggests oxidative degradation. Degradation is confirmed by molecular weight data obtained by E. P. Otocka using gel permeation chromatography as shown in Table I. Both weight- and number-average molecular weights are seen to decrease as cracking progresses. That this degradation is oxidative is demonstrated by the infrared data of Figure 9, obtained by M. G. Chan using an attenuated total reflectance technique[7] on the outer surfaces of several insulations. The absorptions at 1710 and 1735 cm^{-1} are indicative of the relative amounts of oxidation in the polyethylene. Initially only the 1735 cm^{-1} band appears, then as oxidation progresses the 1710 cm^{-1} absorption becomes the more prominent, often tending to obliterate the initial band, as is the case with the laboratory-oxidized control of Figure 9. Unexposed insulation, or insulation which has remained protected by the cable sheath, shows only the weak 1735 cm^{-1} absorption normally seen in the spectra of most polyethylenes. The spectra for insulations removed from the pedestal, on the other hand, show strong 1710 cm^{-1} bands, indicating that substantial oxidation has taken place.

The involvement of copper, demonstrated by Hawkins et. al.,[2] is again confirmed by the spectra of Figure 10, where the inner surface of the same green insulation shows an absorption at 1580 cm^{-1} characteristic of an organo-copper complex. This is quite strong in the spectrum for the oxidized portion from the pedestal, but barely visible in that of the unoxidized section where the insulation was protected by sheath. This band is not present in the spectra of the outer surfaces in either case.

The molecular weight and infrared data thus confirm that the immediate cause of the field failures is copper-catalyzed oxidative degradation. The available facts also indicate that the opportunity for this degradation probably results from the interaction of a number of variables, not all of which have necessarily been recognized. This is exemplified by the fact that in no pedestal have all the insulations of a given color been found to be degraded. In even the worst cases examined, white insulations have been found side by side, one completely disintegrated, its neighbor still retaining essentially its original physical properties. The question arises whether such insulations may not have been different from the beginning. This enigma remains inexplicable at the present state of knowledge of the phenomenon.

Antioxidant Content of Field Samples

The polyethylene in these insulations was originally stabilized with 4,-4'-thiobis (3-methyl-6-tertiary butyl phenol), known familiarly by its trade-name

"Santonox." Prior to 1959, this antioxidant was used at 0.05% by weight, and after about the middle of 1962 at 0.10% nominal concentration. During the interim, either concentration may have been present in a given insulation.

The presence of a sulphur atom makes it possible to analyze for Santonox in two different and independent ways. On the one hand, determination of total sulphur content indicates the combined sum of spent plus unspent antioxidant, while the latter alone can be determined directly by ultraviolet spectroscopy or by various chromatographic and colorimetric methods. It can be determined indirectly and conveniently by differential thermal analysis (DTA) through use of a calibration curve.

The total Santonox content (i.e. spent plus unspent) of 28 field samples is shown in Figure 11. The most interesting feature of these data is not so much the great spread in values as the fact that the failed samples are all relatively high in sulphur, and therefore presumably in original stabilizer content. The uncracked samples show greater variability in total sulphur, many of them retaining substantially less than required for the nominal 0.10% Santonox present originally. As seen in Figure 12, none of the field wires have significant residual amounts of active stabilizer, both failed and unfailed samples showing less than 100 p.p.m., which is too little to be determined accurately by DTA or by most other methods. The one sample cross-checked by gas chromatography did fortuitously agree at 0.008% by both methods.

These seemingly paradoxical data provide an important clue to the probable immediate cause of these particular failures. The initial temptation to suggest, on the basis of the high sulphur content of the failed wires, that Santonox is actually the initiator of the failures can safely be disregarded. The high sulphur content actually has a quite different significance. As will be demonstrated shortly, Santonox has only a very limited solubility in solid polyethylene, just enough to assist it in diffusing to the surface where it can be lost. Its oxidation products (the sulphur-containing residues remaining after it has been oxidized in the course of its function as an antioxidant) are, on the other hand, known to be high-melting and very insoluble[8]. Presumably they are therefore non-migratory. On this basis, the high sulphur content of the failed wires is direct evidence that their antioxidant content was used up at some very early stage, before diffusion and migration could begin to operate, thus maintaining their sulphur content essentially as it was in the raw material. At the other extreme, the insulations which have survived in the field are evidently those whose antioxidant was, for some unexplained reason, not consumed at the same early stage, but which survived long enough for a substantial part of it to migrate out of the polymer and be lost. These insulations would, then, appear to have gone into the field with a higher level of active stabilization than those which failed and would, for this very reason, have survived longer. On this basis the data, instead of being paradoxical, become very logical. The important unknown is the reason for the difference in initial consumption of antioxidant.

Migration of Santonox

The ideal antioxidant would be one soluble enough in polyethylene at use temperatures to preclude any tendency toward migration. Above the melting point of the polymer, many of the commonly used stabilizers, Santonox included, exhibit such solubility. Below the solidification range, and particularly below about 80°C, the solubility characteristics of polyethylene change drastically, and at ordinary temperatures few materials give evidence of being soluble in it beyond perhaps a few parts per million. This is the worst possible condition, providing both the impetus for exclusion of the solute and a modus operandi for its migration.

It is a simple matter to demonstrate loss of stabilization with time in Santonox-containing polyethylenes. In Table II for example, DTA induction times over a period of years are shown for several insulations shelf-aged on their copper conductors, and for one example of a natural inner sheath never in contact with metal. Substantial decreases in stability have been observed in laboratory test sheets in the absence of metal. An example is shown in Table III, where progressive loss of stabilization is seen to begin after only about five hours.

The reason for this behavior can be seen in the micrographs of Figure 13, the originals of which were taken at 1200X in a scanning electron microscope by Bair[9]. Figure 13A shows the surface of an unaged film of low density polyethylene containing 0.10% Santonox. The only features visible are striations reflecting surface markings of the aluminum foil against which the film was molded. Figure 13B shows the same film after five days at 70°C, with its surface now covered with crystals readily identified as Santonox by taking a profile across the field with an electron probe to produce a sulphur scintillation pattern which corresponds precisely with the boundaries

of the crystals.

Beyond question, Santonox migrates readily to the surface of polyethylene, from which it can be removed and lost by a number of physical processes. The key factor is temperature. This migration is a phenomenon which takes place in polyethylene only below its melting point, and which appears, on the basis of limited data, to be most prominent in the region of approximately 50-70°C. Above the melting point of the polymer, Santonox is completely miscible with and soluble in polyethylene at the concentrations normally used. At such temperatures it can be used up by oxidation, and small amounts may be lost by volatilization, but it will not display the massive exclusion which operates in the solid state.

This characteristic is not unique to Santonox, but is displayed to greater or lesser extent by most of the commonly used antioxidants, the differences being controlled by individual solubility limits and diffusion rates. Migration, or blooming, appears to be a major factor in limiting the effective lifetimes of these materials as stabilizers for polyethylene under actual use conditions. Since it does not occur at temperatures above the melting point of the polymer, meaningful predictions of solid state lifetimes cannot possibly be made on the basis of high temperature data alone.

As an example, Figure 14 shows an Arrhenius-type plot of DTA induction time vs. temperature for the Irganox 1010/OABH* combination presently being used as an interim replacement for Santonox. The DTA data were obtained by K. C. Weyts over the range 140-210°C using preoxidized copper dishes in an atmosphere of pure oxygen. The line established by least squares fit extrapolates to 204 years for loss of induction time at 70°C. The slope can be interpreted as showing an effective activation energy of 39.5 kcal/mole for the combination of processes involved. Oxygen absorption data on the same sample by Mottine[10] over the range 120-180°C when plotted similarly give values of 193 years at 70°C and 38.2 kcal/mole apparent activation energy. The two sets of data are in very good agreement, yet when this insulation is actually placed in a 70°C circulating air oven it is found to lose its induction time in only 90 days. Thus, the life expectancy extrapolated from the high temperature data is proven to be overoptimistic by some three orders of magnitude. A major factor contributing to the discrepancy is obviously the inability of the high temperature tests to sense the powerful contribution of stabilizer migration.

* cf. Table IV for chemical identification.

Recognition of this problem in polyethylene stabilization focuses attention on the solubility characteristics of the additives used. It becomes clear that a nonmigratory stabilizer must be either completely soluble in solid polyethylene at normal use temperatures, or totally insoluble. The worst possible situation is a low level of solubility of the kind exhibited by most of the available antioxidants, because this provides a built-in mechanism for carrying the material out of the polymer. The prospects for finding a stabilizer that has high solubility in polyethylene at ordinary temperatures (i.e. below about 70°C) do not appear particularly good. Complete insolubility, such as is exhibited by carbon black, appears to be a more practical goal. Insoluble non-black materials with antioxidant activity are not presently available, so the stabilizer combinations discussed in this paper must be considered as interim improvements, to be used only until more permanent systems can be devised.

Copper Inhibitors

Oxanilide was the first copper inhibitor proposed for use in polyolefins[11]. It has been found to have two short-comings: excessive volatility[12], and the toxicity of its vapors. When the decision was made to use an inhibitor, the only one known to be suitable for use in electrical grade polyethylene and commercially available was N,N'-dibenzal-(oxalyl dihydrazine)[13], better known as OABH. This inhibitor is effective, moderately permanent, and considered safe for use on the basis of acute inhalation toxicity studies. A number of other metal deactivators are available, but many of them are unsuitable for use in polyolefin insulations because they are too fugitive, are ionic in nature, or have other deficiencies.

A small group of experimental and semi-commercial inhibitors has been examined, but none appear to be more effective or more permanent than OABH, although some may offer potential economies. Their vapor toxicities have not been determined. Figure 15 shows the performance of these inhibitors relative to OABH in the presence of CHA 1035 as the antioxidant. In this chart and the succeeding one, the length of the bars indicates the relative effectiveness of the stabilizer combination, while the number of bars indicates its permanence. Since the chemical structures of these materials have not been released for publication, they are identified only by code designations.

It is readily apparent that while several of them are essentially equivalent to OABH in performance, none is sufficiently better to warrant exploitation. The possibility must, of course, be recognized that what is actually being tested here is the permanence of the antioxidant, or perhaps of an antioxidant-deactivator complex, rather than that of the metal deactivator per se. Since the deactivators exhibit no antioxidant activity of themselves, loss of the primary antioxidant means failure of the combination.

Other Antioxidants

Figure 16 shows similar data for a few of the more effective antioxidant/OABH combinations examined, using Santonox as a basis for comparison. Five of these stabilizers can be considered essentially equivalent to Irganox 1010 in improvement over Santonox. One, AgeRite White, is outstandingly better in these tests. However, none of these combinations, including the AgeRite White/OABH, exhibits the level of permanence at 70°C believed necessary to insure a 40-year service life under the most severe field conditions. The basis for this pessimism becomes clear if one assumes that the equivalent of first order reaction kinetics is involved (i.e. that the rate of stabilizer depletion will be halved for every 10°C drop in temperature), and that a mean effective temperature for the Arizona region would be about 40°C[2]. This provides a factor of only 8X between 70° and 40°C. Thus, these materials must all be viewed only as possible candidates for interim use.

The Role of Pigments

Figure 8 appears to confirm earlier indications[1,2,14] that pigmentation is one of the variables which can affect oxidative service life. Detailed studies of the pigments believed to have been used, particularly carbon black, are under way. Results will be reported at a later date, but at this point, a minor contribution on the role of titanium dioxide can be put on record.

The data of Table V show the effect of titanium dioxide on the oxidative stability of low density polyethylene when tested at 200°C by differential thermal analysis. The type of titanium used is found to be of major importance, with only the zinc-containing non-chalking type detrimental to stability at 200°C. The adverse contribution of zinc is confirmed by the data for Sample E, where 1.0% of the oxide was added, producing a very substantial decrease in induction time. The two non-zinc-containing grades of titanium dioxide exhibit DTA induction times consistent with that of the natural control (Sample A) within the reproducibility of the test method (22±2 minutes). Since the non-chalking grade of titanium has presumably never been used in Bell System insulating compounds, these data suggest that the abnormal failure rate for white insulations may be attributable to causes other than the presence of this pigment. It should be noted that the DTA tests were run at approximately processing temperature, where the chemistry may admittedly be different from that operating under field conditions. The results of low temperature aging studies now in progress should indicate whether similar conclusions apply in the solid state.

Summary

A field survey of some 1100 terminals has shown that degradation of polyethylene insulations is widespread in pedestal-type installations in the warmer parts of the country. No cracked insulations have been found in Bell System aerial plant.

Temperature is quite obviously a factor in these failures, but careful measurements indicate that the pedestals exceed 55°C only on infrequent occasions.

Cable age is also a factor, but obviously not the controlling one, since no cracked insulations have been found in plant installed prior to 1958 and since degradation in more recent cables does not conform to any pattern related to age.

Wall-thickness of the insulation plays some role, with the thinner walls of the insulations on 24 and 26 gauge conductors showing about twice as many failures as those on the thicker 19 and 22 AWG sizes.

Pigmentation also appears to have an effect because white and red insulations show twice the disintegration rate of any of the other light colors, while no black insulations have cracked in the field to date. If titanium dioxide, present in all except the black insulations, is a factor in this behavior, its contribution may be ascribable to the presence of small amounts of zinc in one of the standard grades available. The likelihood that this grade of titanium dioxide has actually been used in Bell System insulations appears to be remote, however, leaving the possible role of non-black pigments indefinite at this point.

Gel permeation chromatography demonstrates that the cracked insulations have been degraded in molecular weight, and infrared absorption spectography confirms that this degradation is due to copper-catalyzed oxidation.

It is demonstrated that Santonox, due to its very limited solubility in solid polyethylene, very quickly migrates to the surface of the polymer, from which it can be lost by a number of physical processes. Aging tests at temperatures below the melting range of the polymer show that this is true for most of the available stabilizers.

The fact that the disintegrated samples show high sulphur content (equivalent to about the maximum amount of Santonox normally found in the raw material) suggests very strongly that essentially the entire stabilizer content of these cracked insulations must have been used up at some very early stage in their history. The stabilizer in their mates which have remained uncracked in the same pedestals appears, for reasons unknown, to have survived substantially longer.

It is shown that the usual Arrhenius-type extrapolation of high-temperature data can lead to predictions of oxidative service life potential at normal use temperatures which are overoptimistic by several orders of magnitude. This presumably comes about because the contribution of stabilizer migration in the solid state cannot be reflected in this extrapolation.

Finally, data are presented on the permanence at 70°C of some improved stabilizer combinations suitable for interim use in polyethylene insulating compounds pending development of truly permanent systems. The ideal stabilizer is defined as one either completely soluble or totally insoluble in solid polyethylene at use temperatures. The very slight solubility exhibited by most of the available stabilizers is adjudged the worst possible characteristic from the standpoint of permanence.

Acknowledgments

The information presented in this paper is the result of a team effort. The work of certain individuals is identified in the text, but contributions have been made by a great many other members of Bell Laboratories, of Western Electric, and of Bell System operating companies. It is impractical to include all these individuals by name, but their valuable assistance is nonetheless gratefully acknowledged.

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Mr. Howard is a graduate of the Sheffield Scientific School of Yale University, where he received a B.S. in organic chemistry in 1936. Since that time he has been a Member of Technical Staff of Bell Laboratories, working in various aspects of rubber and plastics chemistry and technology. He is currently supervisor of the group responsible for plastics on wire and cable.

Mr. Howard is author of numerous publications on plastics and rubber and has had several patents issued to him. He is active in standards work for the Plastics Industry in ASTM Committees D-11, D-20, and D-24. He is a fellow of the American Institute of Chemists and a member of the Society of Plastics Engineers, the Wire Association, the American Chemical Society, and of Alpha Chi Sigma.

Figure 1 - Geographic Distribution of Degraded Insulations

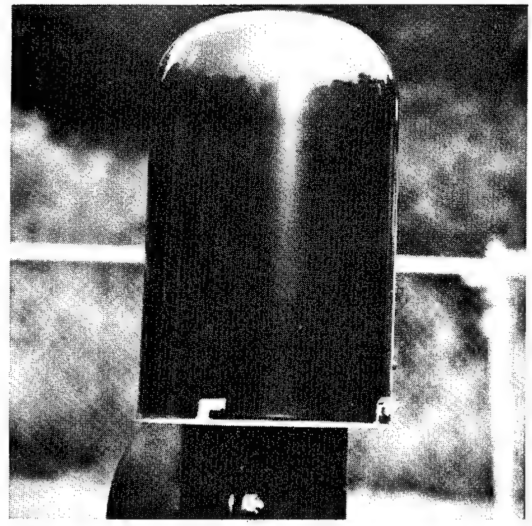


Figure 2 - Typical "B" Pedestal - Closed

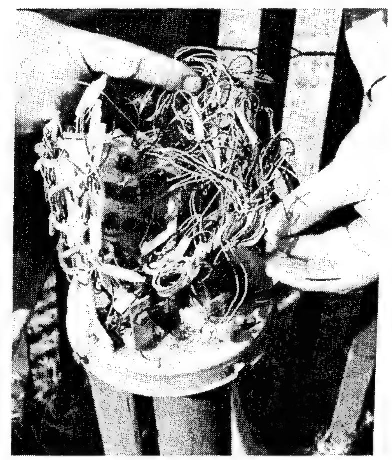


Figure 3 - Typical "B" Pedestal - Cover Removed

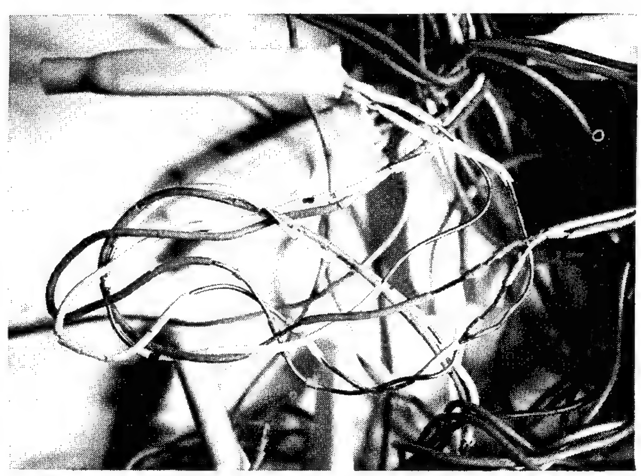
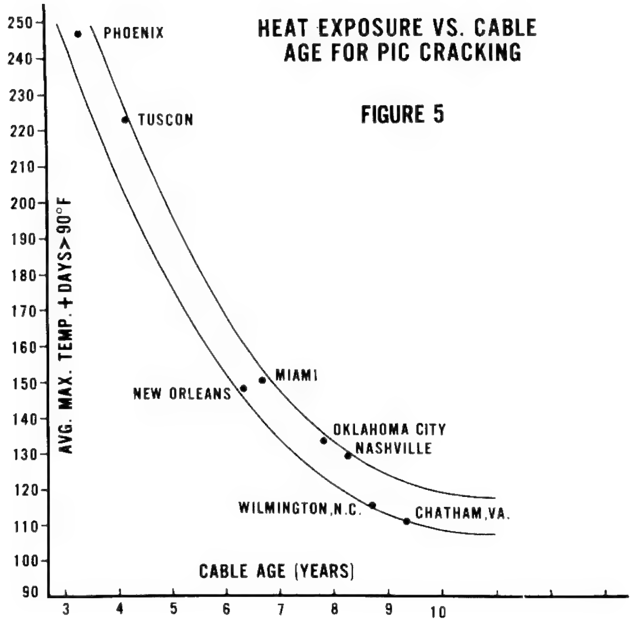
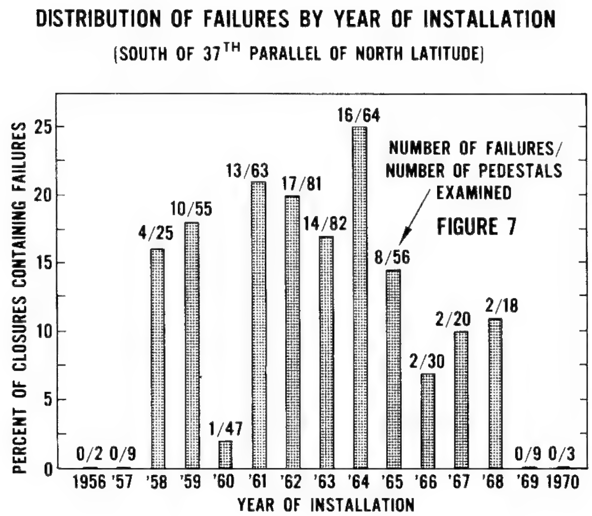
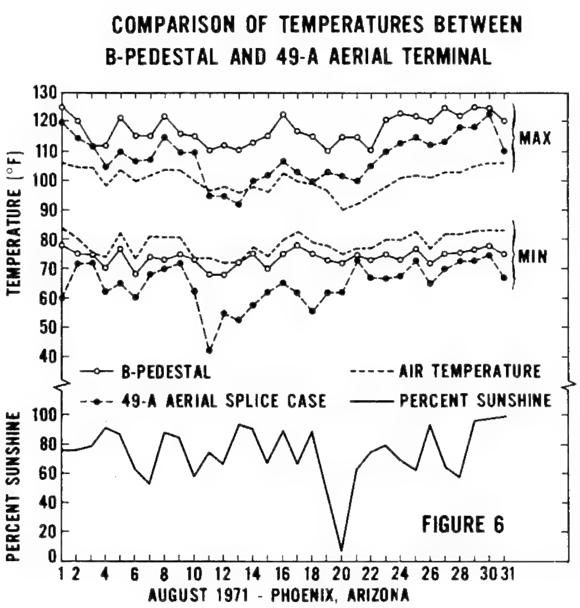
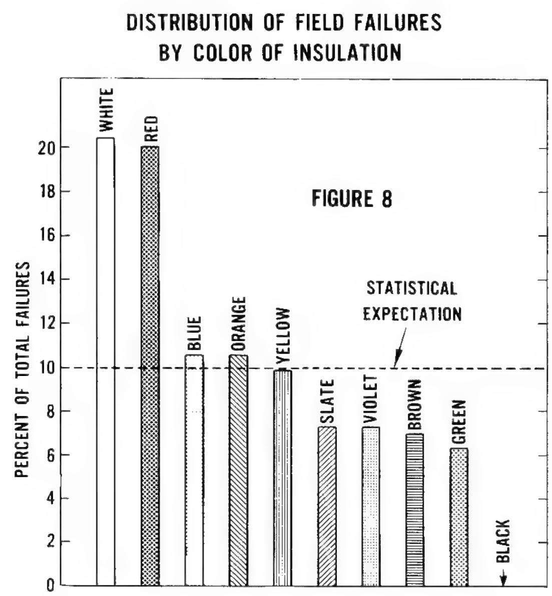


Figure 4 - Example of Degraded Insulation


HEAT EXPOSURE VS. CABLE AGE FOR PIC CRACKING
FIGURE 5
PHOENIX
TUSCON
MIAMI
NEW ORLEANS
OKLAHOMA CITY
NASHVILLE
WILMINGTON, N.C.
CHATHAM, VA.
AVG. MAX. TEMP. + DAYS > 90°F
CABLE AGE (YEARS)


DISTRIBUTION OF FAILURES BY YEAR OF INSTALLATION
(SOUTH OF 37TH PARALLEL OF NORTH LATITUDE)
FIGURE 7
NUMBER OF FAILURES/
NUMBER OF PEDESTALS
EXAMINED
PERCENT OF CLOSURES CONTAINING FAILURES
0/2 0/9
4/25
10/55
1/47
13/63
17/81
14/82
16/64
8/56
2/30
2/20
2/18
0/9 0/3
YEAR OF INSTALLATION


COMPARISON OF TEMPERATURES BETWEEN
B-PEDESTAL AND 49-A AERIAL TERMINAL
MAX
MIN
TEMPERATURE (°F)
B-PEDESTAL
49-A AERIAL SPLICE CASE
AIR TEMPERATURE
PERCENT SUNSHINE
FIGURE 6
AUGUST 1971 - PHOENIX, ARIZONA


DISTRIBUTION OF FIELD FAILURES
BY COLOR OF INSULATION
FIGURE 8
PERCENT OF TOTAL FAILURES
WHITE
RED
BLUE
ORANGE
YELLOW
SLATE
VIOLET
BROWN
GREEN
BLACK
STATISTICAL
EXPECTATION

IRS ABSORPTION DATA FOR 26 AWG INSULATIONS FROM TUCSON FAILURE

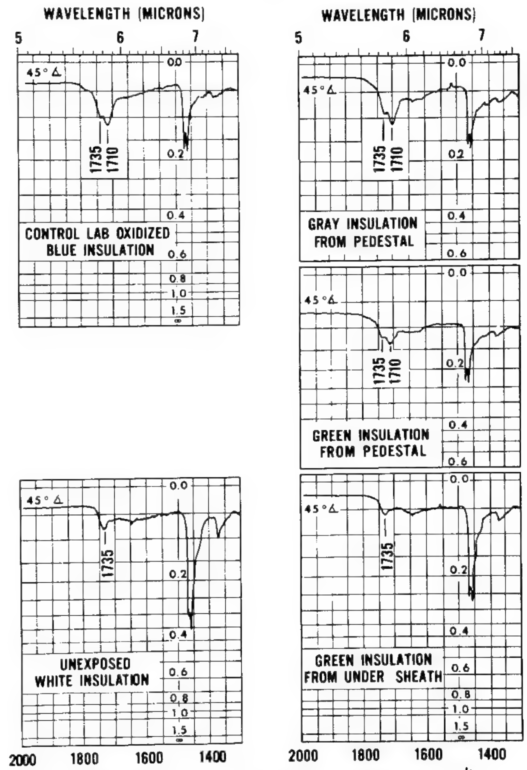


FIGURE 9

IRS ABSORPTION DATA FOR 26 AWG GREEN INSULATION FROM TUCSON FAILURE

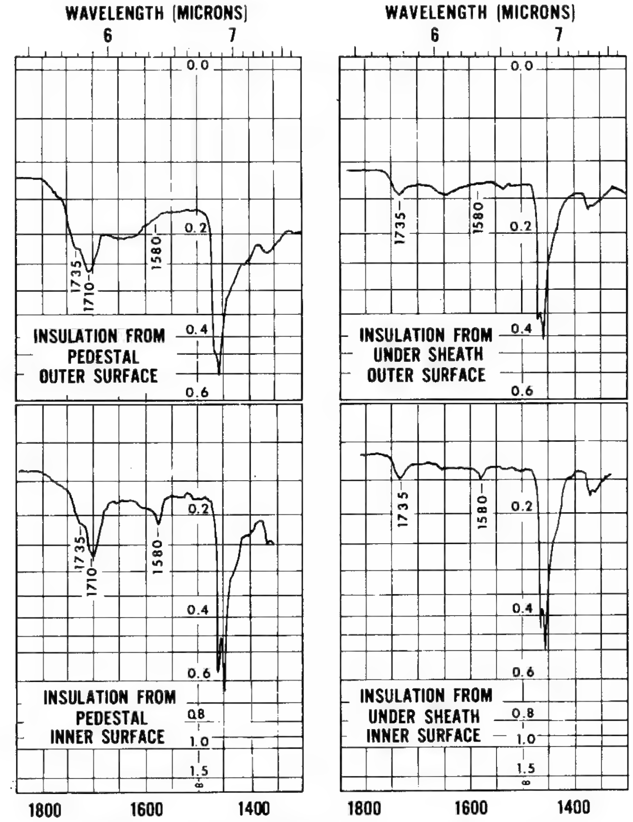


FIGURE 10

TOTAL SANTONOX CONTENT OF FIELD SAMPLES BY SULFUR ANALYSIS

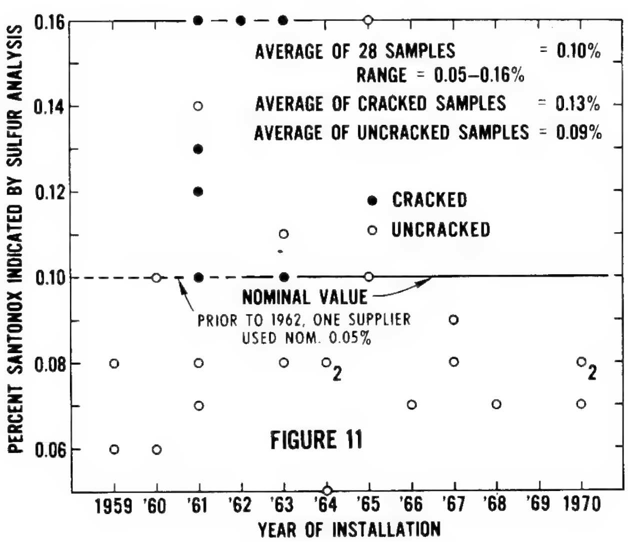


FIGURE 11

DTA INDUCTION TIMES FOR INSULATIONS FROM TERMINALS IN THE FIELD

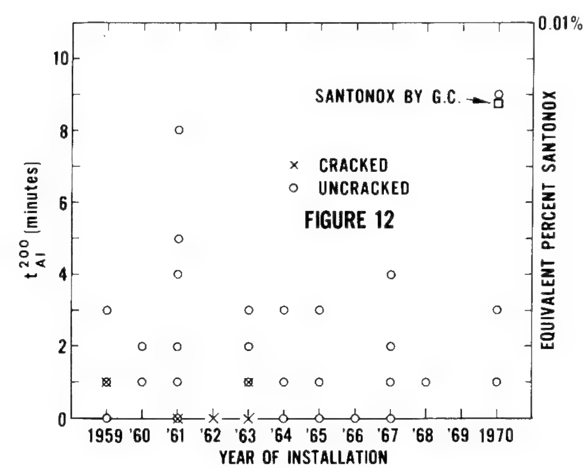
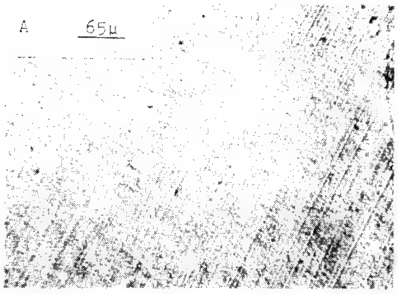
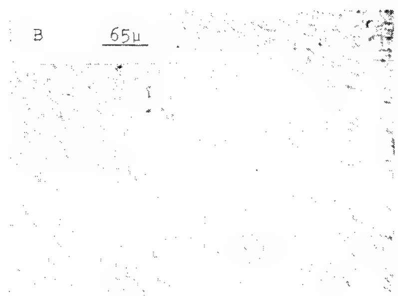


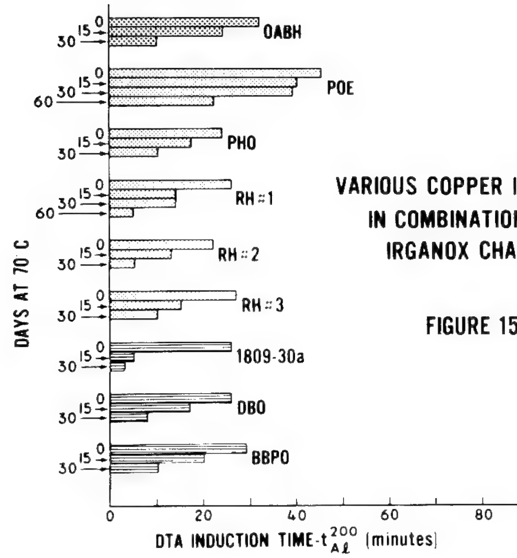
FIGURE 12



ORIGINAL



5 DAYS AT 70C



VARIOUS COPPER INHIBITORS IN COMBINATION WITH IRGANOX CHA 1035

FIGURE 15

PERSISTENCE AT 70°C OF ANTIOXIDANTS IN COMBINATION WITH OABH

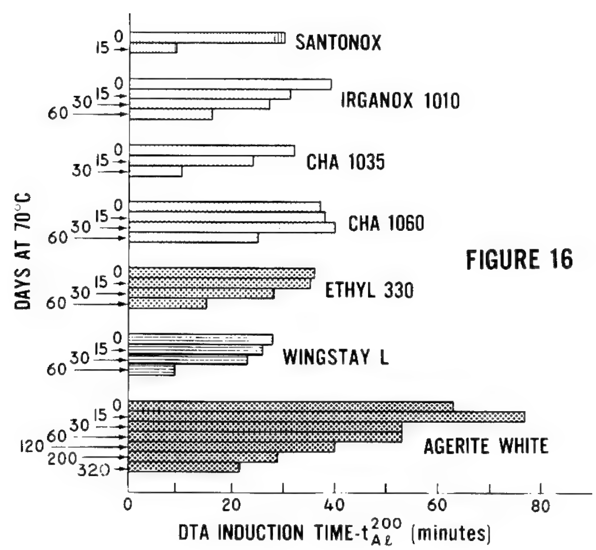


FIGURE 16

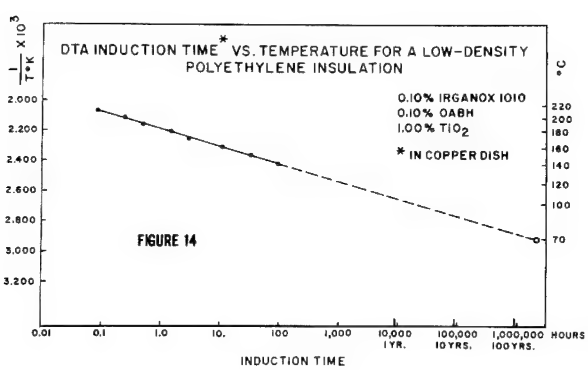


FIGURE 14

TABLE I

GPC Molecular Weight Data for Field Samples of Polyethylene Insulation

Sample	Location[a]	Color	$\bar{M}_w$ [b]	$\bar{M}_n$ [b]	Condition
Unexp. Control	-	Natural	1.5×10^5	3.0×10^4	OK
P7007305	Tucson, Ariz.(P)	Blue	1.3×10^4	4.5×10^3	Many Cracks
"	" " (S)	"	1.2×10^5	1.8×10^4	OK
P7104314	Laguna, Cal. (P)	Blue	4.6×10^4	9.8×10^3	Few Cracks
"	" " (P)	White	6.5×10^4	8.8×10^3	" "
P7104315	" " (P)	Blue	1.2×10^4	4.8×10^3	Many Cracks
"	" " (P)	White	1.0×10^4	2.4×10^3	" "
P7104316	" " (P)	Blue	1.6×10^5	3.0×10^4	OK
"	" " (P)	White	1.3×10^5	3.0×10^4	"
P7104317	" " (S)	Blue	8.0×10^4	2.4×10^4	"
"	" " (S)	White	1.6×10^5	2.9×10^4	"

[a] P = Insulation in pedestal (no sheath)
S = Insulation under sheath

[b] Unpublished data of E. P. Otocka

TABLE II

Change in DTA Induction Time of Shelf-Aged Polyethylene Stabilized with Santonox

Sample	Color	Size	DTA Induction Time (Minutes)[a] 1/66	10/67	9/68	9/70
P6601007	White	19 AWG	28			5
P6601009	Red	19 AWG	36		29	
P6601013	White	19 AWG	32		19	10
P6709199	Slate	19 AWG		26		10
P6709202	Black	19 AWG		28		11
P6709203	Violet	19 AWG		24		8
P6510323	Natural	Inner Sheath	63			28

a Aluminum dish in oxygen at 200°C

TABLE III

Change in DTA Induction Time of Freshly Prepared Polyethylene/Santonox Compound[a]

Run #	Time Lapse Since Preparation	DTA Induction Time (Minutes)[b]
1	1 hr.	31
2	2 hr.	30
3	2 3/4 hr.	31
4	3 3/4 hr.	29
5	4 1/2 hr.	30
6	5 1/3 hr.	22
7	6 hr.	22
8	7 hr.	21
9	6 mo.	16

Range:	First 4 1/2 hr.	29-31 min.
	First 7 hr.	21-31 min.
	6 mo.	16-31 min.

a-0.10% Santonox by weight

b-Aluminum dish in oxygen at 200°C

TABLE IV

Chemical Identification of Stabilizers

Antioxidants	
AgeRite White[a]	Sym. di-β-naphthyl-p-phenylene diamine
Ethyl 330[b]	1,3,5-trimethyl-2,4,6-tris (3,5-di-t-butyl-4-hydroxy benzal) benzene
Irganox 1010[c]	Tetrakis [methylene 3-(3',5'-di-t-butyl-4'-hydroxyphenyl) propionate] methane
Irganox 1035[c]	Proprietary hindered phenol
Irganox 1060[c]	Proprietary
Santonox[d]	4,4'-thiobis(3-methyl-6-t-butyl phenol)
Wingstay L[e]	Polymeric hindered phenol
Copper Inhibitor	
OABH[f]	N,N'-dibenzal-(oxalyl dihydrazide)

TABLE IV

Footnotes

a-R. T. Vanderbilt Company, Inc.
b-Ethyl Corporation
c-Ciba-Geigy Corporation
d-Monsanto Company
e-Goodyear Chemical Division
f-Eastman Chemical Products, Inc.

TABLE V

Effect of Titanium Dioxide on
Stability of Polyethylene

Polyethylene[a]	100.00	100.00	100.00	100.00	100.00
Irganox 1010	0.10	0.10	0.10	0.10	0.10
Titanox RANC[b]	--	1.00	--	--	--
Titanox RA-40[c]	--	--	1.00	--	--
Titanox RA-50[d]	--	--	--	1.00	--
Zinc Oxide	--	--	--	--	1.00
DTA t_{Cu}^{200} (minutes)[e]	22	12	21	24	7

a - ASTM Type IA5

b - "Nonchalking" grade: Si-, Al-, Zn-coated

c - Fine particle-size rutile

d - General purpose rutile

e - In oxygen, using preoxidized copper dishes, and with conductor left in place

HIGH DENSITY POLYETHYLENE INSULATION FOR FILLED TELEPHONE CABLES

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SUMMARY

A change in the traditional antioxidant used for high density polyethylene insulation provides much improved stability to insulation used in contact with petrolatum-based fillers in waterproof telephone cables. Oven-aging data are presented to show that HDPE insulation should be at least as stable as the polypropylene insulations now in use.

The mechanical properties of HDPE insulation appear not to be degraded by lengthy contact with filler at the maximum anticipated field temperatures (70°C).

Optimum performance of any insulation is obtained by careful selection of filler composition; low-oil petrolatums are recommended.

INTRODUCTION

In past discussions of filled cable technology at the Wire and Cable Symposium, the experiences with polypropylene and with low or medium density polyethylene insulation materials have received the most attention, with only occasional reference to high density polyethylene for this application. The present paper is offered as a progress report on the evaluation of HDPE for use with petrolatum-based cable fillers as an alternative to polypropylene in the United States.

It is not intended that emphasis on HDPE should imply that medium density insulation materials commonly in use in other countries are less suitable, however, it is recognized that of the polyolefins commonly in use in the United States (low and high density polyethylene and polypropylene), low density polyethylene has serious limitations in the filled cable application because of high levels of filler absorption and polymer swelling at elevated temperatures. On the other hand, high density polyethylene absorbs considerably less filler than low density polyethylene and even less than polypropylene (Figure 1). This is one basic reason for considering HDPE.

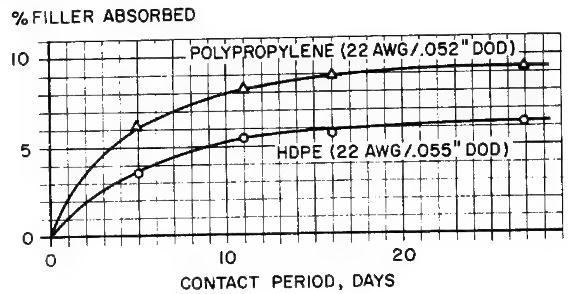

FIGURE 1, ABSORPTION OF 92/8 PJ/PE FILLER BY INSULATION AT 70°C

A second advantage of HDPE is the greater stability of the polymer molecule to oxidation as a result of the relatively few branch points along the chain. It is reasoned that HDPE with only about 4-5 branches/1000 C atoms should be easier to stabilize in the critical filled cable application than LDPE with about 25 branches/1000 C atoms or polypropylene which is branched at every other carbon atom.[1]

The stabilization of insulation is complicated by the catalytic effect of copper conductor on the oxidation process. For many years, the effect of copper on the oxidation of polypropylene has been recognized, and metal deactivators have been recommended to provide prolonged lifetimes.[2] Until very recently, polyethylene was considered to be relatively unaffected by copper catalysis. As a result of recent pedestal failures of LDPE insulation, however, more work has been done to try to understand the factors leading to oxidative failure of polyethylenes and there does appear to be a significant contribution of copper. Again, the effect seems to be greatest in those materials having the greatest amount of chain branching (polypropylene >> LDPE > HDPE).

DISCUSSION

The major concern in filled cable systems has been the compatibility of insulation with filler, especially oxidative stability in a pedestal environment and the retention of physical properties after long-term filler exposure.

In any discussion of compatibility, it is necessary to establish the conditions of use for the cable and then select or design materials suitable for these conditions.

Recent field studies[3] indicate that pedestal temperatures reach a high of about 62°C in the Southwest, and another report suggests than an effective mean temperature of 43° applies in pedestals in that location.[4] The latest REA specification for filled cable anticipates a maximum field temperature of 160°F (71°C) in setting limits on compatibility and on filler flow characteristics.

For the oxidation studies reported here, it is assumed that the continuous service temperature for exposed insulation in a pedestal is 43°C. This temperature is used in extrapolation of Arrhenius aging data for predicting insulation lifetimes. For the initial exposure of insulation to filler for oxidation studies and for measuring the effects of filler on physical properties of insulation, the temperature of 70°C has been used.

Antioxidant Selection

The effective stabilization of a polyolefin must satisfy several conditions of use which include protection at high temperatures during processing, resistance to filler contact, and then protection against air oxidation usually in the presence of copper conductor.

In the processing of high density polyethylene, melt temperatures may approach 300°C. As the molten polymer exits from the die, lower molecular weight antioxidants tend to volatilize reducing the concentration available for protection in service. For the filled cable application it was deemed necessary first to upgrade normal antioxidant systems, e.g., thiobisphenols, by use of less volatile antioxidants. It was then found that addition of a metal deactivator helped to prolong the lifetime of insulation after contact with petroleum jelly-based fillers.

As indicated in Table I, antioxidant volatility decreases with an increase in molecular weight. The data shown were measured by thermal gravimetric analysis (TGA) on neat antioxidant samples. Santonox, which has commonly been used in polyethylene insulation for many years, suffers over 50% weight loss at 550°F. Weight loss with several of the higher molecular weight stabilizers is negligible.

TABLE I

VOLATILITY OF ANTIOXIDANTS AT 550°F (TGA)

Antioxidant	Molecular Weight	% Weight Loss
DBPC	220	100
Santonox (Monsanto)	358	56
Topanol CA (ICI)	544[a]	17
Wingstay L (Goodyear)	b	11
Goodrite 3114 (Goodrich)	783	<5
A/O 330 (Ethyl)	775	<5
Irganox 1010 (Ciba-Geigy)	1178	<5
Metal Deactivators		
Oxanilide		65
Mark 1475 (Argus)		<5
OABH (Eastman)[c]		<5
GI-09-367 (Ciba-Geigy)		<5
Bisphenyl oxanilide		<5
Conditions		
Sample Size	~.012G	
Heating Rate	20°C/Min.	
Atmosphere	N_2, 500 cc/Min.	

[a] Contains 10-15% lower MW by-product.

[b] Condensation product, 1-4 aromatic rings. Weight loss is mainly monophenol.

[c] Licensed under US Patent 3,440,210

Metal deactivators also must be selected in part on the basis of low volatility. Oxanilide, for example, sublimes at extrusion temperatures, thereby reducing its effective concentration.

The final selection of antioxidant systems was based mainly on the results of oven aging tests over the temperature range of 70-160°C. There was some use of differential scanning calorimetry (DSC) induction times for screening or monitoring purposes.

The oven aging approach was chosen because it most nearly simulates field exposure, and the end point (brittleness) is clear-cut and meaningful, which is not always the case with alternate test methods such as oxygen-uptake. DSC measurements are useful for comparing stabilizer systems for effectiveness at high temperatures (processing conditions) but the induction times do not necessarily relate to the effectiveness at lower (field) temperatures. Several examples are given in Table II to illustrate this poor correlation with oven-aging results. The data for Santonox in this table also point out that the addition of a metal deactivator does not always insure improved performance.

TABLE II

LIFETIME AT 120°C VS DSC INDUCTION TIMES

FOR WHITE HDPE FILMS

Antioxidant[a]	DSC Induction Time, Minutes[b]	Time to Brittleness at 120°C, Days[c]
Santonox	2.6	14
Santonox/MD1	24.0	13
AO-A	14.0	31
AO-B	14.0	12
AO-C/MD1	14.0	5
AO-D	>30	17
AO-A/MD1	30.0	76

[a] Each component at 0.1% concentration.

[b] 200°C, 500 cc air/min., copper pans.

[c] .010 inch film on copper foil.

In this laboratory, screening tests by oven-aging are conducted on .010 inch films containing the antioxidants and white pigment. The films are aged at 120° in contact with copper foil until cracking occurs on flexing. The effect of filler contact is determined by oven-aging after exposure to filler for 7 days at 70°C.

The best systems are then scaled-up for tests on wire insulation which is oven-aged over the full temperature range of 70-160°C. At the highest temperature (140 and 160°C) straight lengths of wire are tested. Below the polymer melting temperature, pigtail specimens (wire coiled about its own diameter) are used. With the pigtails, spontaneous cracking of any portion of the specimen is taken as the failure point.

The aim in the selection of an antioxidant system was that the performance in oven-aging tests after filler contact at 70°C should be at least equivalent to the performance of standard HDPE insulation used in air-core cables without filler contact and at least equivalent to the performance of commercial polypropylene insulations after filler contact. Arrhenius time-temperature data for an acceptable HDPE system is shown in Figure 2 compared with standard HDPE (no filler) and with a polypropylene insulation obtained from the field in mid-1971.

The lower line represents white HDPE stabilized with 0.1% Santonox. The predicted lifetime at 43°C is above 100 years. The data for HDPE with an improved antioxidant system, consisting of a high molecular weight stabilizer and a metal deactivator, and for polypropylene show roughly equivalent performance at high temperatures after filler contact, but the polypropylene exhibits a deviation from linearity at lower temperatures, suggesting that the lifetime at field temperatures would be less than that of HDPE and possibly less than would be required for the application.

The data of Figure 2 point out a weakness of extrapolating to field temperatures: there is always uncertainty that a linear relationship holds for the full temperature range. As an alternative to waiting for failure at lower temperatures, such as 70°C, which might require several years of oven-aging, several laboratories are investigating a method which involves oven-aging at low temperatures in combination with DSC measurements at higher temperatures. It is reasoned that as insulation is aged at low temperatures, the stabilizers will lose some of their effectiveness. The extent of the loss in effectiveness can be indicated by the high-temperature DSC measurements. A plot of time of aging against DSC induction time should allow extrapolation to essentially zero induction time which will give the corresponding lifetime at the aging temperature.

Use of this method at low temperatures has not progressed far enough in our laboratory to report on its utility; however, early use of the method at 120°C gave results which suggest that some stabilizer systems do not lose effectiveness linearly with time of aging so that extrapolation would be uncertain. Data for several stabilizer systems in white HDPE are shown in Figure 3 to illustrate this point.

If the data for system 4 had been extrapolated to zero induction time after 15 days of aging, the predicted lifetime would have been only about one-half of the measured lifetime (brittleness).

Studies of this nature will continue at lower temperatures for insulations with and without filler contact.

Effect of Filler Composition on Insulation Stability

There has been some interest in cable fillers composed entirely of low molecular weight polyethylene or based on polybutylenes, but the most commonly used fillers make use of petroleum jelly (PJ). In the United States, a polyethylene component is added to PJ to control flow characteristics and consistency. PJ and PE/PJ mixtures provide a useful balance of properties at low cost, but they have been a cause of major concern to polyolefin suppliers and cable designers alike because of the compatibility problems. The fillers under conditions of elevated temperature cause swelling, softening and loss of

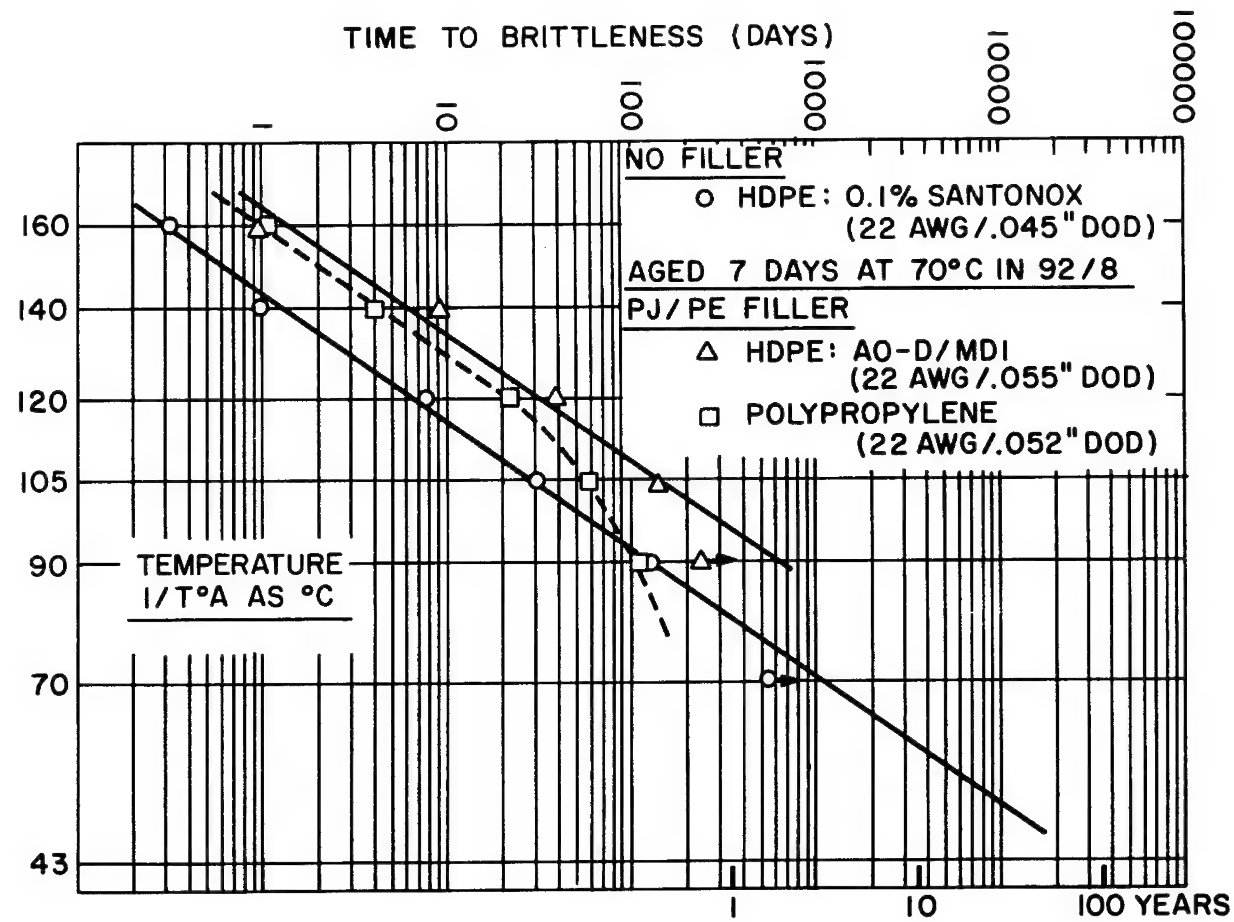

FIGURE 2, OVEN AGING OF WHITE INSULATION

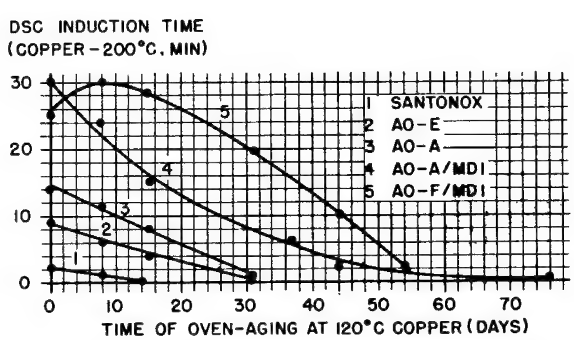

FIGURE 3, EFFECT OF OVEN AGING ON DSC INDUCTION TIME OF WHITE HDPE FILMS

mechanical properties of insulation and jacketing materials, and they seriously influence the oxidative stability of insulation.

There has been a move from the initial 85% PJ - 15% PE mixtures using high-oil PJ and Santonox stabilizer to mixtures containing less PE (8-10%), low-oil PJ, and better-performing stabilizers. This move was made partly because of changes in industry standards for flow temperature from 80° to about 70°C, but the major reason was a need to improve the stability of the polypropylene insulation which contacted the filler.

In our tests on polypropylene (Figure 4) the improvement in stability was significant between 85/15 and 92/8 fillers, especially at lower temperatures. The 85/15 filler made use of high-oil PJ and contained 0.2% Santonox. The 92/8 filler used low-oil PJ and contained 0.5% Irganox 1010. Still better performance was observed when an unmodified PJ from the United Kingdom was used.

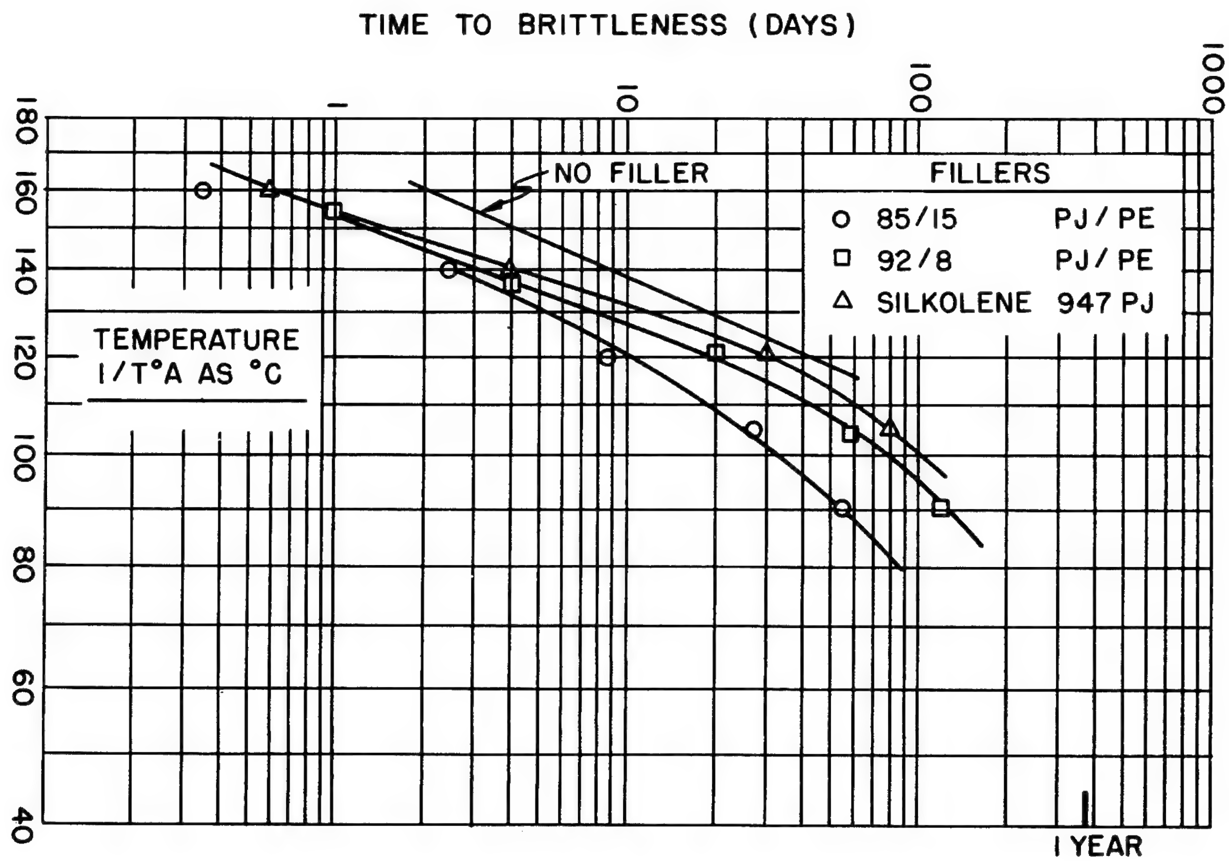

FIGURE 4, OVEN AGING OF POLYPROPYLENE INSULATION (22 AWG/.052" DOD) AFTER EXPOSURE TO FILLER FOR 7 DAYS AT 70°C

TABLE III

EFFECT OF FILLER COMPOSITION ON STABILITY OF WHITE HDPE INSULATION

Filler Composition[a]	Insulation AO	Wire Size	Days to Brittleness at 120°C
None	Santonox	19 AWG/.058" DOD	8
85/15 PJ/PE	Santonox	"	5-7
None	AO-D/MD1	"	59
85/15 PJ/PE	"	22 AWG/.055" DOD	19-21
92/8 PJ/PE	"	"	40
"	"	19 AWG/.058" DOD	36
PJ-Silkolene 947	"	22 AWG/.055" DOD	57

[a] Filler exposure, 7 days at 70°C.

In all cases, the deviation from linearity mentioned earlier was observed and pedestal lifetime would be difficult to predict.

For the HDPE with improved stabilizer (Figure 2) the effect of filler composition on stability also is marked. Complete Arrhenius data are not yet available, but oven aging results at 120°C are given in Table III. Data for HDPE stabilized with Santonox are listed also for comparison.

The 92/8 PJ/PE filler and the Silkolene PJ filler provide a higher level of stability than does the 85/15 PJ/PE filler; in fact, there appears to be no loss of stability with the PJ filler as compared to the control without filler. These results tend to confirm the claims made last year at this Symposium[5] that certain fillers enhance the stability of polyethylene insulation materials.

Effect of Filler on Physical Properties of Insulation

In the studies of oxidative stability, the objective was to determine the fate of insulation which had been exposed first to filler and then to air to simulate a pedestal environment. There also is interest in the physical effects of longer term contact of filler with insulation in the absence of air at elevated temperatures such as might be experienced when cable is stored in sunlight or used in aerial service.

A test is nearing completion (6 months) in which HDPE insulation has been exposed to 92/8 PJ/PE filler in stoppered tubes at 70°C. At intervals, measurements of tensile elongation (at room temperature) are made on wiped insulation. After 4 months, no change in elongation was observed. See Table IV. Other specimens exposed under the same conditions for 30 days continued to meet REA requirements for shrinkback and cold bend.

TABLE IV

EFFECT OF FILLER ON ELONGATION OF HDPE INSULATION[b]

Time of Exposure, Days[a]	% Elongation, 2"/Min.
0	530
7	630
30	670
60	840
120	650

[a] At 70°C.

[b] 22 AWG/.055" DOD.

The toughness of HDPE also does not appear to be altered by exposure to filler at 70°C. Specimens of insulation which had been used in filler absorption tests reported earlier (27 days exposure) were tested for cut-through resistance (1/2" wedge), crush resistance (2" plate) and abrasion resistance using a square-bar abrader with a 1 pound weight. In this series, comparisons were made with a polypropylene insulation.

The results are given in Table V. There was essentially no loss in toughness for the HDPE insulation. As expected, polypropylene exhibited higher levels of toughness, but the

TABLE V

EFFECT OF FILLER EXPOSURE ON INSULATION TOUGHNESS

		HDPE[a]		POLYPROPYLENE[b]	
		ORIGINAL	EXPOSED[c]	ORIGINAL	EXPOSED[c]
WEIGHT INCREASE, %		-	6.2	-	9.3
COMPRESSION CUT-THROUGH, LBS		27	25	40	31
ABRASION RESISTANCE, LBS/2 INCH		1140	1166	2450	1316
ABRASION RESISTANCE, CYCLES TO FAIL	1 LB	30	29	69	50

[a] 22 AWG/.055" DOD
[b] 22 AWG/.052" DOD
[c] 27 DAYS AT 70°C IN 92/8 PJ/PE

change in toughness was greater than for HDPE after filler contact.

In another test which was proposed by workers at Bell Telephone Labs[6], HDPE and polypropylene insulation were exposed to filler at 70°C for 24 hours, wiped and formed into pigtails. The pigtails were notched down to the conductor across the coils and then aged at 70°C in air. Neither insulation exhibited propagation of the cut or other cracking failures after 30 days, at which time the test was discontinued.

Insulation Economics

At the time this paper was written, the evaluation of HDPE insulation for filled cables by most cable producers was only in the preliminary stages which consisted mainly of laboratory studies of compatibility and extrusion studies; a complete comparison of cable costs with HDPE and polypropylene insulation was not available to the author.

Theoretically, the higher density and higher dielectric constant of HDPE suggest the need for heavier walls, with resultant greater usage of HDPE than polypropylene. Calculations of wall thickness for a given mutual capacitance show, at most, the need for a 1 mil heavier wall for HDPE on 19 AWG conductor with smaller differences on fine wire. Under these conditions, the usage of HDPE would be about 12% greater than for polypropylene. However, the cost of polypropylene presently is 50% higher than for HDPE so there is an advantage for HDPE.

Total cable cost, of course, must take into account not only the insulation requirements but also the usage of filler, shielding and jacketing components. It is not expected that these factors will be the same for all cable producers, so cost comparisons must be made on an individual basis.

CONCLUSIONS

On the basis of oxidative stability, good retention of physical properties at maximum anticipated field temperatures, and economics, high density polyethylene is at least equivalent to polypropylene insulation for use in telephone cables filled with petrolatum-based flooding compound.

For both insulation materials, the performance depends on the selection of an antioxidant system optimized for the specific application and on the selection of filler compounds which minimize the loss of oxidation stability that usually occurs with filler contact.

Future evaluation of filled cable systems requires the development of testing procedures which will allow more confidence in the predicted lifetimes of insulation at pedestal temperatures of 30-60°C.

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NON-EXTRACTABLE STABILISERS FOR POLYPROPYLENE AND POLYETHYLENE INSULATION OF FULLY-FILLED CABLES

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SUMMARY

A method is described of stabilising thin polyethylene or polypropylene insulation on copper conductors utilising a new type of stabiliser which, when incorporated into polyethylene or polypropylene, is made non-extractable by processing above 210°C. The new stabiliser is shown to function as both antioxidant and copper inhibitor.*) Technical comparison with the current practice is made and possible developments based on the use of the new stabiliser are discussed.

INTRODUCTION

The use of selected cellular polyethylene insulation in conjunction with special grades of petroleum jelly filling compounds, as originally adopted in the UK, continues to provide the optimum design of waterproof telephone distribution cables.[1-4] Cables made with this economic combination of materials have most satisfactory waterproof characteristics, long-term stability of electrical characteristics and long life, together with important advantages in handling during manufacture and jointing. Satisfactory service in the field under a wide variety of climatic and environmental conditions, now extending over a period of more than six years, continues to corroborate the results obtained from long-term accelerated tests conducted in the laboratory.

*)An insulated electrical conductor having an insulating layer formed of an olefine polymer containing a stabilising amount of the new type of stabiliser and a fully-filled cable comprising one or more of such stabilised insulated conductors are the subjects of pending patent applications filed in the United Kingdom, the United States of America and in other countries.

Laboratory investigations are continuing on many aspects of filled cables. One such test programme, now in its fourth year, is studying the long-term performance of cellular insulation in filling compounds and includes laboratory tests designed to verify the predictions concerning the question of transfer of petroleum jelly into the cells of the insulant. To date, at temperatures up to the cable operating temperatures, results have been completely reassuring, but these and other aspects pertaining to normal telephone cables will be reported to a future symposium.

The work now reported on non-extractable stabilisers was initiated to solve problems which may arise when the concept of fully-filled cables is extended outside the present field of application.

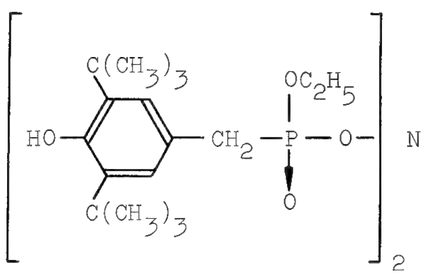
POLYETHYLENE INSULATION

For present applications, a cellular polyethylene insulation with petroleum jelly filling compound gives more than adequate mutual capacitance stability and a low loss tangent.[4] With a different type of hydrocarbon filling compound even the initial equilibrium swelling of the insulation (which occurs soon after manufacture) can be eliminated and an even lower loss tangent can be obtained over a wide spectrum of frequencies. However, the use of such filling compound would up to the present time have resulted in a cable with an unsatisfactory life due to extraction of the stabiliser from the insulant by the filling compound.

It has now been found that polyethylene insulation protected by a

new type of non-extractable stabiliser retains its high resistance to ageing after contact with different types of hydrocarbon filling compounds. These include even the compounds of the polybutene type which cause a rapid and drastic loss of resistance to oxidation of the conventionally stabilised polyethylene.[3]

The new method of stabilisation is based on incorporating into the polyethylene a nickel compound belonging to a group of nickel derivatives of hydroxybenzyl phosphonic acid and in particular nickel bis(3:5-ditertiary butyl-4-hydroxybenzyl phosphonic acid monoethylate). Although more conventionally used as a UV stabiliser,



this nickel compound has been found to function as an effective non-extractable inhibitor of thermal oxidation.

Laboratory tests have established that, provided appropriate compounding and processing conditions are used (with temperatures in excess of 210°C), the nickel derivative incorporated in the polyethylene insulation undergoes oligomerisation and becomes highly resistant to extraction by filling compounds and water. Its performance as a stabiliser in thin polyethylene insulation is illustrated in Table I giving the results of accelerated ageing tests at 105°C. While the evaluation of the new system is still in progress the results show that the nickel compound functions as an effective antioxidant for polyethylene in the presence of copper. It can be used alone or in combinations with low cost commercial phenolic antioxidants.

In its oligomeric form the nickel stabiliser exhibits excellent compatibility with polyethylene: even at 0.5% concentration it showed no tendency to diffuse out of the polyethylene insulation and form surface "bloom" at temperatures from 23° up to 105°C, in contrast to some antioxidants in current use, e.g. antioxidant B or certain alkylated thiobisphenols, whose compatibility limits, especially in the 50°-70°C temperature range, lie below 0.1% w/w.

At the practical concentrations this stabiliser has no significant effect on the dielectric properties of the insulation (loss tangent and resistivity).

Test data in Table I (Core Nos. 1 to 3) confirm the earlier conclusions[3,4] that the conventional antioxidants, including combinations of high molecular weight phenolic antioxidants with copper inhibitors, are ineffective in protecting polyethylene insulation which had been in contact with commercial filling compounds of the polybutene (S, S/1 and S/2) or the petrolatum blend (U/1) type. After immersion in these fillers, the new extraction-resistant stabilisation system can protect the 8 mil thick polyethylene insulation (on copper conductor) against the onset of oxidation at 105°C for a period of at least 1000 hours, corresponding to an expected life of about 50 000 hours on continuous exposure to air at 70°C. With this degree of resistance to oxidation, ageing performance approaches that of the conventionally stabilised polyethylene insulation after contact with the selected grades of petroleum jelly compounds currently used in the UK (cf. Table I, Core No. 10). For reference, induction periods of 1500 to 2500 hours at 105°C [3,4] (and of over 16 000 hours in laboratory ageing tests at 80°C) are achieved.

From the point of view of chemical stability of the insulation, the new stabilisation system permits the use of various hydrocarbon blends, including mixtures with polyethylene, in cables for distribution networks. Many of these compounds, however, have specific technical disadvantages of which the most frequently found are lack of physical stability, leading to separation of the components, and poor waterproofing characteristics as compared with the petroleum jelly compounds, and they all lead to a more expensive cable construction.

TABLE I

Resistance to Oxidation of Polyethylene Insulation

After Two Weeks Immersion in Filling Compounds at 70°C

(8 mil solid white insulation on 24 AWG copper wire)

Core No.	Polymer	Stabilisation System (Nominal Concentration)	Filling Compound	Induction Period at 105°C (Hours)	
				No Air Flow	With Air Flow
1	PE-2	0.2% A	None S S/2 U/1	2000 190 200 * 200 *	900 100 70 * 50 *
2	PE-1	0.15% A + 0.1% C-1	None S S/1	1600 330 < 90	880 130 50
3	PE-3	0.1% B + 0.1% C-2	None S S/1	2700 550 120	1600 + 400 80
4	PE-2	0.1% X	None S/2	1020 720	- -
5	PE-2	0.2% X	None S/2	1570 + 1200 +	1100 700
6	PE-2	0.1% A + 0.1% X	None S/2	1570 + 1100	- -
7	PE-2	0.1% A + 0.2% X	None S/2 U/1	1570 + 1240 + 1200 +	1530 + 1270 + 1000
8	PE-2	0.15% A + 0.2% X	None S Water **	3860 + 1700 1800 +	3470 + 1200 -
9	PE-1	0.2% A + 0.2% X	None S S/1 Water **	3860 + 1100 + 1100 + 1800 +	1800 1350 700 -
10	PE-1	0.08% A	P*** R****	1800 2160	- 2000

Notes:
- * Insulation containing nominally 0.13%A
- ** Two weeks immersion in water at 75°C
- *** Two weeks immersion at 80°C
- **** Six weeks immersion at 80°C
- \+ Test continues

POLYPROPYLENE INSULATION

Since temperatures above 70°C do not occur in any part of any telephone distribution network, there is no reason to design higher temperature cables for this application. The work on polypropylene was started to explore high temperature designs of fully-filled cable which could be required in future for specialised applications such as communication and signalling cables laid alongside certain types of power cables.

Conventionally Stabilised Polypropylene Insulation

The problem of adequate long-term chemical stability has been one of the major technical difficulties hindering the development of satisfactory polypropylene insulation for use in fully-filled cables. Conventional multi-component stabilisation systems now available, comprising synergistic mixtures of antioxidants in combination with copper chelating agents (copper inhibitors), can confer satisfactory resistance to oxidative degradation on thin polypropylene insulation on copper conductor for service in unfilled cables. However, in fully-filled cables these stabiliser systems fail to provide adequate protection against oxidation of the insulation which had been exposed to air after a period of contact with the hydrocarbon filling compound at service temperatures. This loss of protection occurs mainly because conventional antioxidants readily migrate from the polypropylene insulation into the filling compound. Since the effectiveness of the synergistic antioxidant combinations in polypropylene is often critically composition-dependent, even partial extraction of one component may severely reduce the stability of the insulation.

The resistance to oxidation of conventionally stabilised polypropylene had been found [3-5] to be adversely affected by a wide range of types of hydrocarbon filling compounds. This is further illustrated in Table II (Core Nos.1 to 5) showing the performance of solid polypropylene copolymer insulation on ageing in static air at 105°C before and after immersion in petroleum jelly compounds (Q and R) and polybutene compounds (S and S/2). The stabilisation systems present in Core Nos. 4 and 5 represent formulations currently used in polypropylene insulation on copper conductor. Contact with the above filling compounds reduced the life of the 8 mil insulation by factors of 20 to 50 to a level of 100-200 hours, corresponding to an expected time to embrittlement in air at 70°C of less than 5000 hours.

The results show that the presence of copper inhibitors (C-1 or C-3) in the insulation did little to improve the ageing performance after immersion in the filling compounds.

Data in Table II also provide a further illustration of the contrasting behaviour of polypropylene and polyethylene in their response to the different types of filling compounds. While the resistance to oxidation of polyethylene insulation containing conventional antioxidants is also adversely affected by some hydrocarbon filling compounds, it benefits from contact with certain selected petroleum jelly compounds of the Q and R type.[3,4] In the latter case the loss of antioxidant from the polyethylene insulation by diffusion into the filling compound is more than compensated by the absorption of certain natural constituents of the filling compound which act as oxidation inhibitors effective in the presence of copper. This behaviour has been successfully exploited in the development of polyethylene insulated fully-filled cables in the UK.

Because of its molecular structure polypropylene is intrinsically more susceptible to oxidation than polyethylene and requires very much higher antioxidant concentrations (by a factor of 10), and more powerful synergistic antioxidant systems, to achieve a comparable degree of resistance to oxidative degradation. This difference in the oxidation kinetics probably accounts for the observed lack of response of polypropylene insulation to the filling compounds of the Q and R type: the concentration and activity of the natural inhibitors absorbed by the insulation are inadequate to meet the much more onerous antioxidant requirements of polypropylene.

Novel Stabilisation System for Polypropylene Insulation

A search for improved non-extractable antioxidants for polypropylene insulation for use in fully-filled cables has now resulted in the development of a novel

TABLE II

Resistance to Oxidation of Polypropylene Insulation

Before and After Two Weeks Exposure

To Cable Filling Compounds at 80°C

(8 mil solid natural insulation on 24 AWG copper wire)

Core No.	Polypropylene Copolymer	Stabilisation System	Filling Compound	Induction Period at 105°C * (Hours)
1	PP-1	1% D	None Q R	2500 160 120
2	PP-2	1% D	None Q S/2 **	1450 + 140 400
3	PP-3	1% D + 0.25% C-3	None Q	4800 100
4	PP-2	0.7% E + 0.25% C-1	None Q **	1450 + 260
5	PP-1	1% D + 0.25% C-1	None Q R S	2600 + 200 150 170
6	PP-1	1% D + 0.25% C-1 + 0.25% X	None Q	6400 + 1500
7	PP-1	1% D + 0.5% X	None Q R S	6400 + 2450 2300 1800

Notes:
* Time to embrittlement on ageing in static air at 105°C
** 2 weeks at 70°C
+ Test continues

stabilisation system which overcomes the deficiencies of the conventional stabiliser combinations.

The new system is based on the same nickel derivatives as already described for polyethylene. After incorporation in the polypropylene nickel bis(3:5-ditertiary butyl-4-hydroxybenzyl phosphonic acid monoethylate) undergoes oligomerisation on processing at temperatures above 210°C which converts it into a product of low solubility and highly resistant to extraction by hydrocarbons and water. Initial accelerated ageing tests on moulded polypropylene sheets indicated that the nickel compound can be effectively used in combination with other antioxidants and with or without copper inhibitors, and gives high retention of the resistance to oxidation of the polypropylene after prolonged immersion in cable filling compounds.

The feasibility of the new approach has now been confirmed by laboratory tests on polypropylene insulated wire. Data in Table II (Core Nos. 6 and 7) show that formulations based on the new system offer at least a tenfold improvement over the conventional systems in the retention of the resistance to oxidation at 105°C after contact with a variety of filling compounds at 80°C. Accelerated ageing tests at 105°C on the various experimental pigmented compositions, before and after immersion in filling compounds, are still in progress but the interim results in Table III confirm the effectiveness of the new stabilisation system and show that high residual stability of the polypropylene insulation is maintained on ageing both in static air and under conditions of controlled air flow.

TABLE III

Resistance to Oxidation of Polypropylene Insulation

Before and After Two Weeks Exposure

to Filling Compounds at 70°C

(8 mil solid PP-2 insulation on 24 AWG copper wire)

Colour of Core	Stabilisation System	Filling Compound	Induction Period at 105°C (Hours)	
			No Air Flow	With Air Flow
Natural	0.7% E + 0.25% C-1	None Q S/2	1450 + 260 670	1400 + 200 200
Natural *	1% D + 0.5% X	None Q**	6400 + 1930	4000 + 2000 +
Natural	1% D + 0.5% X	None Q S/2	1450 + 1160 + 1160 +	1420 + 1160 + 1160 +
White	1% D + 0.5% X	None Q S/2	1420 + 1160 + 1160 +	1450 + 1020 + 1020 +
Black	1% D + 0.5% X	None Q	1420 + 1160 +	550 + 960 +
Blue	1% D + 0.5% X	None Q S/2	1160 + 780 + 780 +	650 + 700 + 780 +
White	1% D + 1% X	None Q S/2	1420 + 1060 + 1060 +	1450 + 960 + 950 +
White	1% D + 0.5% C-1 + 0.5% X	None Q S/2	1420 + 1060 + 1060 +	550 + 960 + -

Notes:
* PP-1 polymer
** 4 weeks @ 80°C
\+ Test continues

TABLE IV

Effect of Immersion Time in Filling Compounds at 80°C on the Resistance to Oxidation of Polypropylene Insulation Stabilised with the D + X System

(8 mil natural PP-1 insulation on 24 AWG copper wire)

Immersion Time at 80°C (weeks)	Induction Period* at 105°C (hours)	
	Filler Q	Filler S
0	6400+	6400+
2	2450	1800
4	1930	-
14	1700	950

Notes: * Ageing test in static air
+ Test continues

Table IV shows that polypropylene insulation containing the new stabiliser retains high resistance to oxidation even after prolonged exposure (up to 14 weeks) to the filling compound at 80°C.

Further accelerated ageing tests have been carried out at 123°, 140° and 150°C on polypropylene insulation protected by the new stabiliser formulations. The results are given in Table V. These temperature dependence data are still incomplete but suggest that in the temperature range 105°-150°C the Arrhenius-type plots of log (time to embrittlement) versus the reciprocal of the absolute temperature for the new formulations, both before and after immersion in the filling compound, are straight lines nearly parallel to those for the conventionally stabilised polypropylene insulation (cf. Fig. 1). Extrapolation of such

TABLE V

Effect of Temperature on the Ageing Performance of Polypropylene Insulation Before and After Exposure to Filling Compound Q

(8 mil solid PP-2 insulation on 24 AWG copper wire)

Colour	Stabilisation System	Conditions of Immersion in the Filling Compound	Induction Period * (Hours)			
			105°C	123°C	140°C	150°C
Natural **	1% D	No Immersion 4 Weeks @ 80°C	2570 120	200 + 25	70 *** 5	- -
Natural	0.7% E + 0.25% C-1	No Immersion 2 Weeks @ 70°C	1450 + 260	580 + 50	350 8	- 3.5
Natural **	1% D + 0.5% X	No Immersion 4 Weeks @ 80°C	6400 + 1930	3400 + 550	570 *** 100	230 33
White	1% D + 0.5% X	No Immersion 2 Weeks @ 70°C	1420 + 1160 +	1050 + 360 +	400 100	200 40
Blue	1% D + 0.5% X	No Immersion 2 Weeks @ 70°C δ	1160 + 780 +	1050 + 360 +	500 150	- -
White	1% D + 1% X	No Immersion 2 Weeks @ 70°C	1420 + 1060 +	1050 + 1050 +	670 270	300 -
White	1% D + 0.5% C-1 + 0.5% X	No Immersion 2 Weeks @ 70°C	1420 + 1060 +	1050 + 1050 +	490 180	280 -

Notes: * Time to embrittlement on ageing in static air
** PP-1 polymer
*** Test at 143°C
δ Immersion in filler S/2
+ Test continues

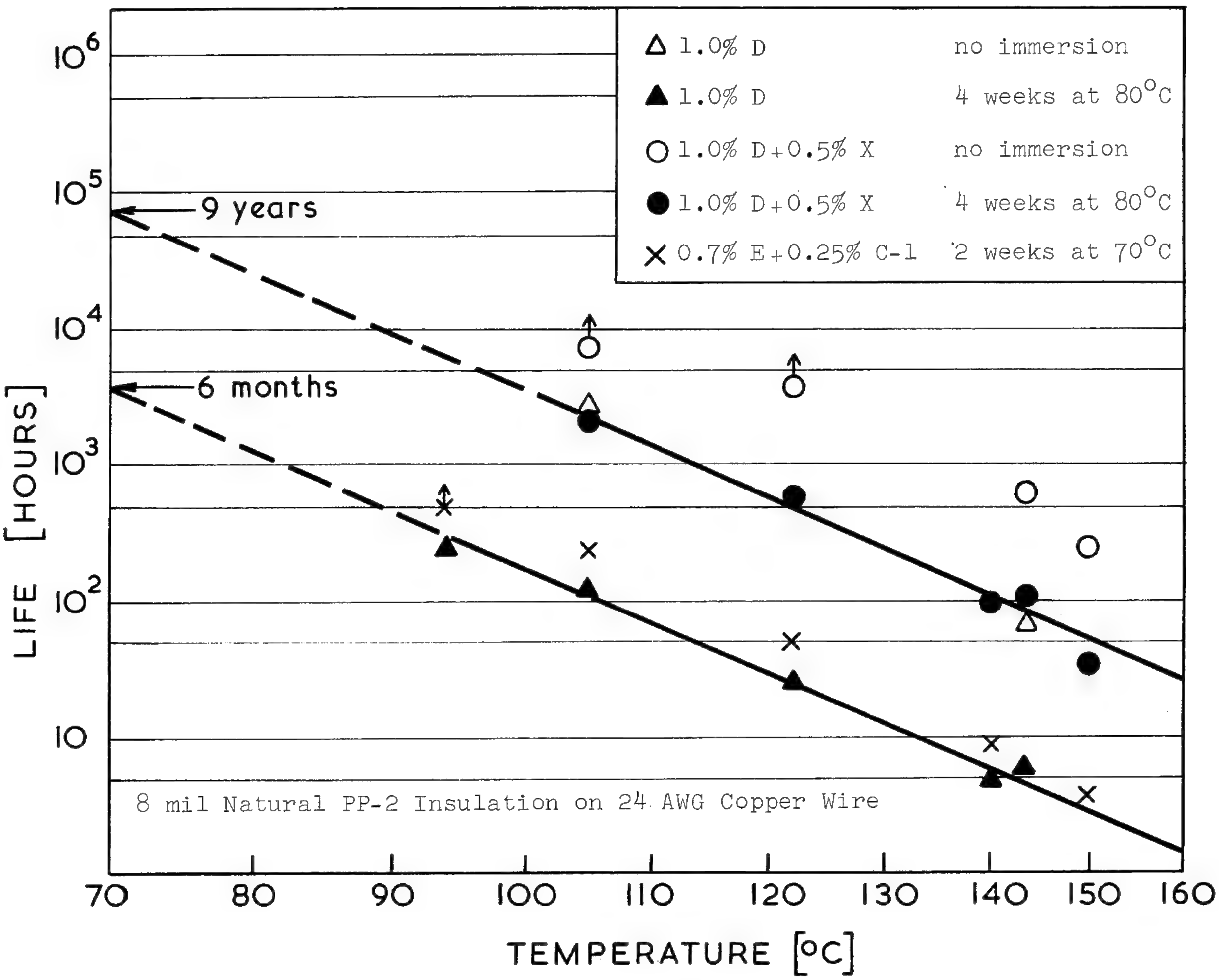


FIG. 1. Temperature Dependence of the Oxidation Induction Period of Polypropylene Insulation After Immersion in Filling Compound Q

plots indicates an expected life of at least 30 000 hours on continuous exposure of the insulation to air at 80°C after prolonged contact with the filling compound.

Data presented in Tables II to V show that the nickel compound is an efficient inhibitor of oxidation of thin polypropylene insulation on copper conductor. It functions as an antioxidant and a copper inhibitor, making the use of additional copper chelating agents in the stabiliser formulation unnecessary. Full benefits of the nickel compound can also be obtained in formulations containing conventional copper inhibitors, providing that certain special compounding procedures are used which minimise the possible reaction between the chelating agent and the nickel compound.

In order to obtain maximum performance from this compound it is essential that the polypropylene should not contain any large concentrations of metal salts since the nickel compound can participate in ion exchange reactions, especially with certain alkaline earth metal salts.

Some care must be taken in the choice of pigments for the new polypropylene formulations since certain metal-containing pigments may react with the nickel compound during processing. No adverse effects have been observed

with titanium dioxide but certain cadmium-containing pigments may be unsuitable.

CONCLUSIONS

A new method of stabilising polyolefines has been developed for protection of thin insulation of PIC and fully-filled cables. For the first time polypropylene insulation can be used with safety in filled cables, since it retains high resistance to oxidation even after prolonged contact with petroleum jelly, or with other hydrocarbon filling compounds. Polyethylene insulation can be similarly stabilised, providing that processing is carried out under conditions which are described. Both types of insulation when stabilised by the new method have high resistance to oxidation in the presence of copper and are resistant to water extraction. For the first time, several types of hydrocarbon fillers can be used with safety, because their deleterious effect on insulation is eliminated, provided that the filling compound itself is effectively protected from oxidation.

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APPENDIX I

MATERIALS EXAMINED

TABLE A

Polyolefine Insulation Materials

Code	Nominal Density (g/cm^3)	Melt Flow Index (g/10 min)
Polyethylene Homopolymers		
PE-1	0.918	0.15*
PE-2	0.927	0.3 *
PE-3	0.923	0.15*
Polypropylene Copolymers		
PP-1	0.905	4 **
PP-2	0.905	0.3 **
PP-3	0.905	0.1 **

Notes: * BS 2782, Method 105 C
** At 230°C/2.16 kg load

TABLE B

Filling Compounds

Compound	Drop Point (°C) IP-31 Method	Drop Point (°C) ASTM D-127 Method (IP-133)	Composition
P	68	76	P.J. of low wax content
Q	75	80	P.J. of high wax content
R	83	-	P.J. of high wax content
S	55	70	Polybutene with some polyethylene and wax
S/1	45	-	Polybutene with some poly-ethylene and wax
S/2	74	-	Polybutene with some poly-ethylene and wax
U	52	69	Petrolatum with polyethylene
U/1	85	-	Petrolatum of lower aromaticity with poly-ethylene

TABLE C

Stabilisers

Code	Chemical Structure & Composition
A	Di-(2-hydroxy-3-α-methylcyclohexyl-5-methylphenyl) methane
B	Pentaerythrityl tetra[β-(3:5-ditert.butyl-4-hydroxyphenyl) propionate]
C-1	Diacetyl adipic acid dihydrazide
C-2	Oxalic acid bis(benzylidene hydrazide)
C-3	Commercial copper inhibitor of undisclosed structure
D	Mixture of 1:1:3-tri(2-methyl-4-hydroxy-5-tert.butylphenyl) butane and dilauryl thiodipropionate (1:1 by weight)
E	Mixture of B and dilauryl thiodipropionate (2:5 by weight)
X	Nickel bis(3:5-ditert.butyl-4-hydroxybenzyl phosphonic acid monoethylate)

APPENDIX II

TEST METHODS

Ageing tests on insulated wire samples in static air at 80°, 95°, 105°, 123°, 140° and 150°C, and under controlled air flow conditions at 105°C, were carried out using test procedures and apparatus similar to those described earlier.[4]

The first signs of oxidative degradation were recorded in all cases. For polyethylene insulation the values of the induction period quoted were recorded as time to the onset of increase in weight (about 0.5% w/w) which was usually accompanied by other evidence of oxidative deterioration (characteristic odour of oxidised polyethylene, discolouration and cracking of the insulation on twisting). In the case of polypropylene the induction period was recorded as the time to embrittlement of the insulation as manifested by either spontaneous cracking or cracking on twisting.

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STABILIZATION OF POLYMERS FOR WIRE AND CABLE APPLICATIONS

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SUMMARY

This paper presents the results of a study of antioxidant and metal deactivator effectiveness in extending the useful lifetime of polyolefin insulating materials. Included are stabilizer systems for low-density polyethylene and poly(propylene-ethylene). The effect of petrolatum filling compound on the stability of polyolefin insulation is discussed. In addition, suitable test methods and criteria used for stabilizer evaluation are reviewed. Methods discussed include oven aging, DTA and oxygen uptake.

INTRODUCTION

Degradation of polyolefin wire insulation by thermally-induced oxidation can seriously threaten the useful field life of these materials. Degradation is manifested as cracking and embrittlement of the wire insulation exposing the copper conductor. Over the last several years recurring evidence of such failures has been reported.[1] Concerns about insulation failures are of main importance at cable joints, terminations, and connections at pedestal or junction boxes. The presence of air, temperatures as high as 160°F, the stressed condition of the insulation, e.g., splices, twists, and contact with copper, result in conditions highly favorable for polyolefin degradation. With the advent of waterproof filled cable an additional influence on thermal degradation is introduced. Filler compounds, of which petrolatum/polyethylene blends are the most widely used, can seriously decrease the resistance to thermal oxidation of the insulation.[2]

It is well known that copper can seriously reduce the thermal stability of polyolefins and is probably the most important influence on the stability of wire and cable insulation. It has been suggested that the catalytic effect of copper is due to the formation of unstable coordina-complexes with alkyl hydroperoxides followed by electron transfer to give free radicals.[4] The mechanism of stabilization of hindered phenolic antioxidants is relatively well known and has been reported previously.[3,4] The mechanism of action of metal deactivators is not well understood. It has been proposed that metal deactivators form inactive complexes with metal ions and/or passivate the surface of solid metals, thus preventing the metal from decomposing the hydroperoxides.

PROCEDURE

Sample Preparation

Additives were incorporated into low density polyethylene and poly(propylene-ethylene) as follows:

1. The polymer was banded on a two roll mill at 250°F for low density polyethylene and at 350°F for poly(propylene-ethylene).

2. The additives were added directly to the banded polymer on the mill and worked for 5 minutes to achieve dispersion.

3. Polymer-copper screen laminates were prepared by inserting an acetone-washed copper screen between two milled sheets and then compression molding. Polyethylene sandwiches were molded at 400°F, contact time - 2 minutes, 220 psi - 5 minutes. Poly(propylene-ethylene) sandwiches were molded at 420°F, contact time - 4 minutes, 220 psi - 3 minutes.

Test Procedures

1. Samples which measured 2" x 1/2" x .010" were cut and oven aged in duplicate on rotating shelves in a forced draft oven. The polymer thickness above and below the copper screen was approximately 5 mil.

   Oven aging of wire insulation was performed using 22AWG copper wire with an insulation thickness of about 5 mils.

2. Samples subjected to filler treatment were dipped in molten filler at 100°C for about 10 seconds, removed and oven exposed without wiping. Since the excess filler dripped off the insulation during exposure, wiping of the samples was unnecessary.

3. DTA evaluations were performed using a DuPont 900 Differential Thermal Analyzer equipped with a DSC cell. Samples were heated at $10^{o}C$/min. on copper pans in nitrogen to $200^{o}C$, oxygen was then introduced at a flow rate of 200 ml/minute and the sample was heated isothermally until the oxidative reaction exotherm was observed. Prior to use the copper pans were pre-oxidized at $200^{o}C$ in O_2 for 10 minutes.

Sample Evaluation

Prior to oven exposure the samples were opaque white. As oven aging progressed discoloration occurred. Successively darker shades of green were apparent with increasing exposure. Blistering, embrittlement and polymer dripping occurred during the last stages of degradation.

Failure of samples was considered as the time at which dark green discoloration or cracking occurred.

Materials

Polymers

Low density polyethylene, wire and cable grade, melt index 2.0.

Poly(propylene-ethylene), wire and cable grade, melt flow 4.0.

Copper Screen

180 x 180 mesh; wire diameter - 2.5 mil; open area 31%.

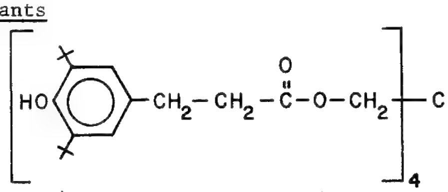
Petrolatum

92/8 petrolatum/polyethylene blend.

Antioxidants

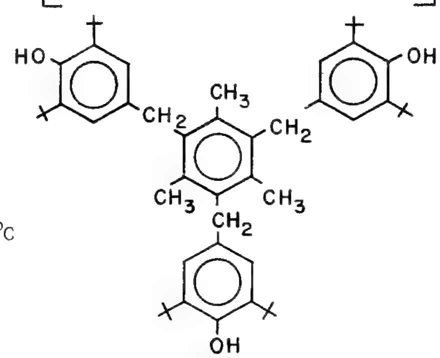
AO-1

m.p. $120^{o}C$



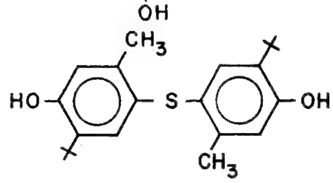
AO-2

m.p. $244^{o}C$



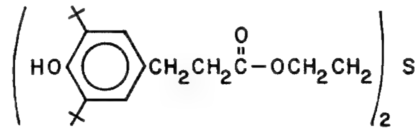
AO-3

m.p. $161^{o}C$



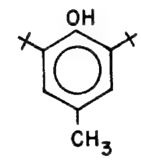
AO-4

m.p. $65^{o}C$



AO-5

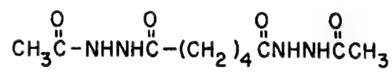
m.p. $70^{o}C$



Metal Deactivators

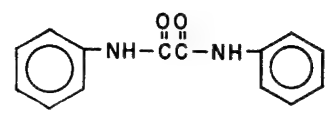
MDA-1

m.p. $257^{o}C$



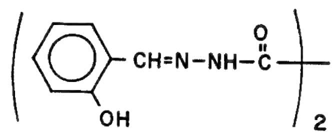
MDA-2

m.p. $251^{o}C$



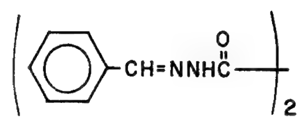
MDA-3

m.p. $327^{o}C$



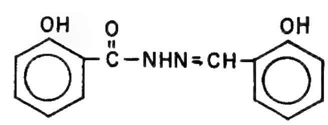
MDA-4

m.p. $320^{o}C$



MDA-5

mp. $283^{o}C$



MDA-6 PATENTS APPLIED FOR; PROPRIETARY AT THIS TIME

RESULTS AND DISCUSSION

Test Methods

Selection of a test method is the most important phase in a stabilizer development program. Of prime concern and perhaps most difficult to achieve is a test method that will enable reliable prediction of useful field life and still enable development of data within a reasonable time. In the wire and cable industry a wide variety of test procedures exists for evaluating stabilizer effectiveness. These include oven aging, DTA, and oxygen uptake. Evaluations are performed generally using insulated wire, polymer copper screen laminates, and polymer containing dispersed copper powder. In investigating the stabilization of the insulation for filled cable, variables that can have a significant effect on performance include, in addition to the stabilizer formulation of the insulation, the filler stabilizer system, the length of contact with filler, temperature of the filler, and filler composition.

In undertaking work on wire insulation stabilization we would have preferred to use wire samples for test purposes since that is the ultimate use form. However, at the time this study was initiated, our laboratories were not yet equipped with wire coating equipment and the preferred insulated wire samples were not available. We thus selected polymer-copper screen laminates for initial testing. We were able to include a limited number of insulated wire formulations in our program which were prepared by outside sources. Current work is being carried out with wire samples prepared on our own equipment. The polymer-copper screen laminates were prepared so that the polymer thickness in contact with the copper screen would be similar to that in wire insulation and thus provide a reasonable simulation.

After reviewing alternate test methods being used for polyolefin wire insulation and after some preliminary work, we selected oven aging at several temperatures for our program. This was done because we felt oven aging would be more relevant to the conditions under which field failures are observed. We considered the other test methods that are used throughout the industry of which DTA and oxygen uptake are the most popular. Although these methods offer more rapid data accumulation than oven aging and should be of value in quality control testing, considerable differences exist between the conditions of the test procedures and those encountered during actual use conditions. Conditions that are of particular concern are as follows:

DTA evaluations require maintaining the test material in a molten form in an atmosphere of oxygen at 200°C. Under these conditions, crystallinity is destroyed and oxygen permeation is substantially increased over that possible in a semi-crystalline polymer. Further, under actual use conditions, air, not oxygen, would be present. The presence of a rich oxygen environment would also be of concern in oxygen uptake tests. The temperatures that are used in DTA and oxygen uptake test procedures are considerably higher than those encountered in the field and would be expected to result in additional degradation mechanisms to those expected at lower temperatures.

Effect of Copper

The influence of copper on the thermal stability of poly(propylene-ethylene) is shown in Table 1. Metal deactivators provide only moderately improved thermal stability of poly(propylene-ethylene)/copper screen laminates at 140°C or 150°C but are very effective at 120°C.

POLY(PROPYLENE-ETHYLENE)

Thermal stability evaluations of poly(propylene-ethylene) were performed using compression molded plaques containing embedded copper screens at 120°C, 140°C, and 150°C. In addition, wire samples were oven-aged with and without exposure to petrolatum/polyethylene filler. The effect of various antioxidants in the filler on the thermal stability of wire insulation was also determined at 140°C. Thermal stability evaluations of the filler itself with various antioxidants were performed using oxygen uptake and color criteria.

Poly(propylene-ethylene) Containing Embedded Copper Screen

The results of oven aging of polypropylene copolymer containing embedded copper screen, (Figure 1), illustrate the marked improvement in stability obtained by several antioxidant/metal deactivator combinations. Addition of metal deactivator to formulations containing antioxidant considerably improves stability at 120°C; the effect of metal deactivator at 140°C or at 150°C is moderate. MDA-6 was the only metal deactivator that significantly improved performance at the higher temperatures. With 0.2% AO-1 at 120°C, MDA-6 was somewhat more effective than MDA-1, MDA-3, and MDA-4, which were about equivalent. MDA-3 was found to discolor in the presence of pigment and is thus of only limited commercial interest.

As with metal deactivators, only moderate improvement in thermal stability was obtained at 140°C or 150°C with most antioxidants (Figure 2). With MDA-3, AO-1 and AO-4 were the most effective antioxidants evaluated.

Various concentrations of antioxidant and metal deactivator were evaluated to determine optimum ratios and total concentrations. Data shown in Figure 3 demonstrate the best performance is obtained when the blend contains a greater proportion of antioxidant than metal deactivator. Blends of 0.35% AO-1 + 0.05% MDA-1 and 0.30% AO-1 + 0.10% MDA-1 resulted in optimum

performance; with MDA-6 a 3:1 AO-1/MDA blend was most effective.

The effect of increasing total stabilizer concentration is shown in Figure 4; with AO-1/MDA-6 or AO-1/MDA-1 blends, considerably improved performance occurs with increases in concentration over a wide range.

Wire Insulation

The relative performance of three metal deactivators in combination with an antioxidant is shown in Table 2. A comparison of these data with those of embedded copper screen evaluations (Figure 5) indicate that considerably longer failure times occur with insulated wire than with embedded copper screen. In insulated wire the effectiveness of MDA-1 is evident even at 150°C and is superior to MDA-2 or MDA-4. As aging temperature is decreased MDA-1 and MDA-4 exhibit about equivalent activity. MDA-2 resulted in reduced thermal stability at all temperatures evaluated.

These data suggest that both temperature and sample form can have a significant effect on metal deactivator effectiveness. The greater severity of plaques containing embedded copper screen compared to insulated wire is probably attributable to differences in contact area of polymer to copper. However, the essentially parallel results for copper screen-polymer laminates and wire samples suggest the laminates will provide useful data.

Evaluations at higher temperatures enable more rapid data accumulation than at lower temperatures and can be useful for determining stabilizer effectiveness. Since the effect of stabilizers are less pronounced at higher aging temperatures, a higher degree of precision would be required to demonstrate significant differences among stabilizer systems.

Effect of Filler Treatment

The insulated wires of Table 2, were dipped in molten petrolatum/polyethylene filler compound at 100°C for about 10 seconds. Wires were dipped in both unstabilized and stabilized material containing 0.5% of AO-1 and then oven aged without wiping at several temperatures.

Figure 6 illustrates the considerable loss in thermal stability after treatment with filler. Treatment of the wire insulation with filler containing 0.5% AO-1 substantially improved stability of all the formulations tested. Of the metal deactivators evaluated, MDA-1 was the only material exhibiting metal deactivating effectiveness after exposure to filler (stabilized or unstabilized).

The loss in thermal stability after exposure to filler is further illustrated by oxygen uptake evaluations shown in Table 3. After prolonged exposure to filler at 70°C, MDA-1 was the only metal deactivator that resulted in improved thermal stability.

Effect of Filler on Thermal Stability of Wire Insulation

The thermal stability of two wire insulation formulations at 140°C after treatment with filler containing various antioxidants is shown in Table 4. AO-1 resulted in the most improvement in stability. With the exception of AO-1, the presence of other antioxidants in the filler compound had virtually no effect on the thermal stability of wire insulation containing a metal deactivator and antioxidant compared to treatment with unstabilized filler.

Thermal Stability of Filler

The thermal stability of the filler compound itself was evaluated using color and oxygen uptake criteria (Table 5). The petrolatum/polyethylene filler undergoes only slight discoloration when aged at 140°C for 170 hours. AO-1 and AO-4 had no effect on color while increased discoloration occurred with AO-3. Color, however, does not seem to be a meaningful indicator of petrolatum stability since the considerable differences in thermal stability between unstabilized and stabilized filler that were evident in oxygen uptake evaluations were not reflected by color differences of these formulations after oven aging. Similarly, comparison of oxygen uptake data with data shown in Table 4 indicate that the relative effectiveness of antioxidants in the filler on the stability of the insulation is not reliably predicted by oxygen uptake evaluations.

It is suggested that the negative effect of the petrolatum may be attributed to the following:

1. Oxidative degradation of the filler compound results in species which can sensitize the degradation of the insulation. Degradation of the filler compound can occur during filling of the cable where the filler compound is heated in holding tanks at 240°F. The filler compound can also be subject to degradation when left on spliced wire ends; even if wiped, a thin film of the filler compound is likely to remain on the insulation.

2. Absorption of the filler compound by the insulation. Polyolefin insulating materials can absorb significant quantities of the filling compound. This absorption can result in introduction of degraded material into the bulk of the insulation as well as resulting in a swelling of the polymer and increased air permeability.

3. Extraction of stabilizers in the insulation by the filler compound.

LOW DENSITY POLYETHYLENE

Thermal stability evaluations of low density polyethylene were performed at 120°C in a forced draft oven using compression molded plaques containing an embedded copper mesh screen. Failure time was considered as the time required for discoloration or cracking of the samples. Additional aging at 110°C, 90°C, and 80°C was performed using low density polyethylene coated copper wire. Samples at 90°C and 110°C were aged as straight unbent wire while pigtails were aged at 80°C to more closely approximate the stressed state that would be encountered under actual use conditions. Failure criteria were comparable to those in molded plaques.

Limited DTA evaluations of low density polyethylene were performed using copper pans in an oxygen atmosphere. Failure was defined as the onset of exotherm after isothermal heating at 200°C.

Results of evaluations at 120°C of low density polyethylene plaques containing embedded copper screen (Table 6) and thermal stability evaluations at 80°C, 90°C and 110°C of low density polyethylene wire (Table 7) demonstrate that the effect of metal deactivator is considerably more pronounced at the lower aging temperatures. MDA-3 and MDA-6 exhibited excellent metal deactivating effectiveness at all aging temperatures. Although only slight activity of MDA-1 was evident at 120°C, it was a highly effective stabilizer when tested at 90°C or 80°C and was comparable to MDA-4 and MDA-6. Similar behavior in wire insulation with increasing temperature was also evident with MDA-4.

Although antioxidants alone can provide improved thermal stability in the presence of copper, the presence of a metal deactivator is needed for optimum stability. Conversely an effective antioxidant is also required even when used in combination with an effective metal deactivator. This is illustrated by the substantially reduced thermal stability of low density polyethylene containing MDA-3 in conjunction with AO-3. AO-1 and AO-4 exhibited about comparable antioxidant activity and were superior to AO-3.

Results of thermal stability evaluations thus indicate that considerably improved performance can be obtained by use of a metal deactivator in combination with an antioxidant; both an effective antioxidant and effective metal deactivator are required. The proper selection of test temperature is extremely important and can result in elimination of stabilizers that could be highly effective during actual use conditions if performance at higher temperatures is poor.

Evaluations of insulated wire at 90°C and 80°C indicate that AO-1 and AO-4 and MDA-1, 3, 4, and 6 are highly effective stabilizers.

Effect of Pigment

Equivalent failure times (embrittlement) occurred with or without 1.0% TiO_2. The color of pigmented samples at failure was dark green while unpigmented samples were blackened (Table 8).

DTA Evaluations

DTA evaluations of unpigmented polyethylene formulations at 200°C, in copper pans, in oxygen, also demonstrated the improved thermal stability obtained with MDA-3 and the inferiority of AO-3 that was observed in low density polyethylene/embedded screen evaluations at 120°C (Table 9). These limited data suggest that DTA evaluations may provide some indication of stabilizer effectiveness at higher temperatures, but were not useful for predicting the excellent thermal stability with AO-1/MDA-1 combinations at lower temperatures.

DTA evaluations of pigmented (1.0% TiO_2), low density polyethylene resulted in comparable failure times for all formulations evaluated and were not effective for demonstrating effectiveness or differences among stabilizer systems. The samples on heating in the DTA cell formed a bead which had only minimum contact with the copper pan.

CONCLUSIONS

1. Antioxidants and metal deactivators can substantially improve thermal stability of low density polyethylene and poly(propylene-ethylene) wire insultation. Both the presence of an antioxidant and metal deactivator are necessary for optimum performance.

2. In low density polyethylene, MDA-1, 3, 4, and 6 were the most effective metal deactivators; AO-1 and AO-4 were the most effective antioxidants.

3. In poly(propylene-ethylene), MDA-1, 4, and 6 were the most effective metal deactivators; AO-1 and AO-4 were the most effective antioxidants.

4. In poly(propylene-ethylene), when exposed to petrolatum/polyethylene filler, AO-1/MDA-1 blends resulted in the best thermal stability.

5. Exposure of poly(propylene-ethylene) to petrolatum/polyethylene filler substantially reduced thermal stability. Improved thermal stability of the insulation is obtained if the filler compound contains an antioxidant. AO-1 was the most effective antioxidant for the filler compound.

6. Oven aging of insulated wire samples or polymer/copper screen laminates is a useful procedure for the evaluation of stabilizers for wire insulation.

7. Oven aging results indicate that the most reliable data are obtained if aging is performed as close to the actual use temperature as feasible; the highest desirable test temperature was 110°C for low density polyethylene and 140°C for poly(propylene-ethylene).

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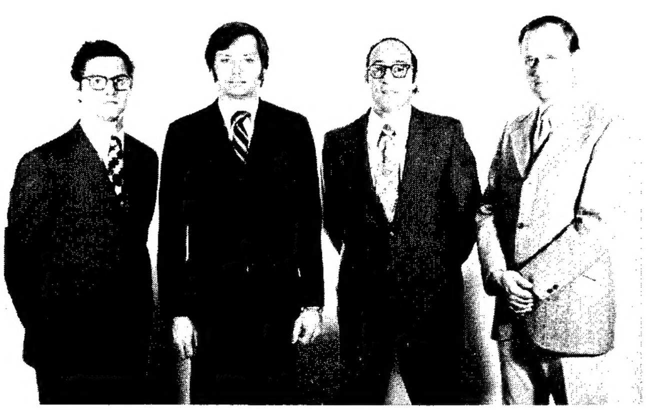

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Peter P. Klemchuk has a B.S. degree from M.I.T. and M.S. and Ph.D. degrees in organic chemistry from Rutgers University. He jointed the Geigy Chemical Corporation in 1960 and is presently Technical Manager of the Polymer Additives Department, CIBA-GEIGY CORPORATION. Dr. Klemchuk is a member of AAAS, ACS and SPE.

FIGURE 1

THERMAL STABILITY OF POLY(PROPYLENE-ETHYLENE) CONTAINING EMBEDDED COPPER SCREEN

0.2% AO-1 + 0.2% MDA

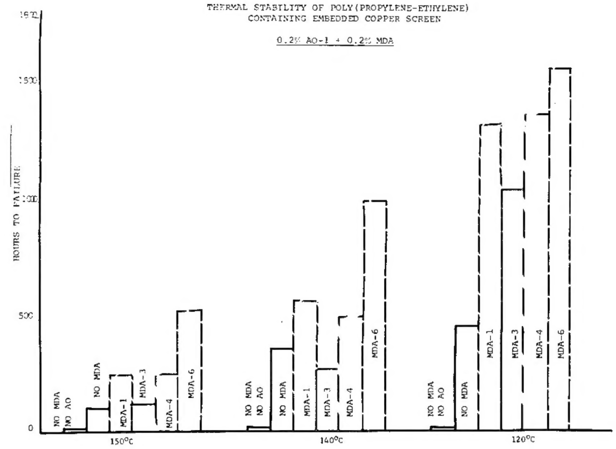

FIGURE 3

THERMAL STABILITY OF POLY(PROPYLENE-ETHYLENE) WITH EMBEDDED COPPER SCREEN

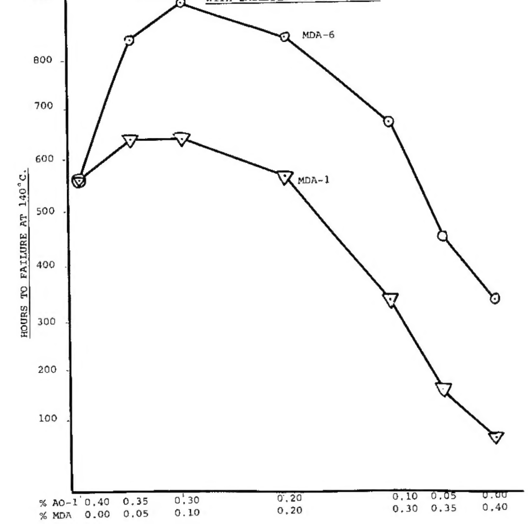

FIGURE 2

THERMAL STABILITY OF POLY(PROPYLENE-ETHYLENE) EMBEDDED COPPER SCREEN

0.2% MDA-3 + 0.2% AO

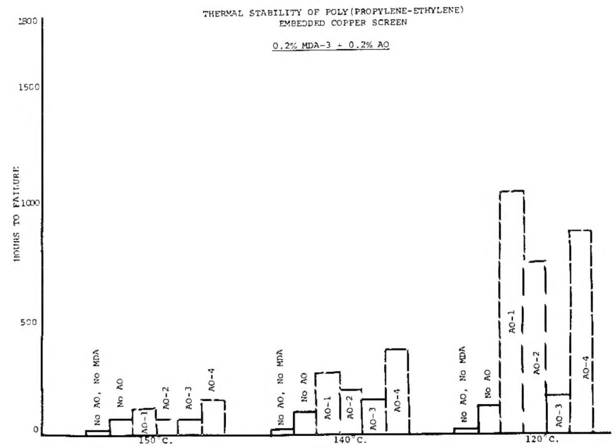

FIGURE 4

THERMAL STABILITY OF POLY(PROPYLENE-ETHYLENE) WITH EMBEDDED COPPER SCREEN

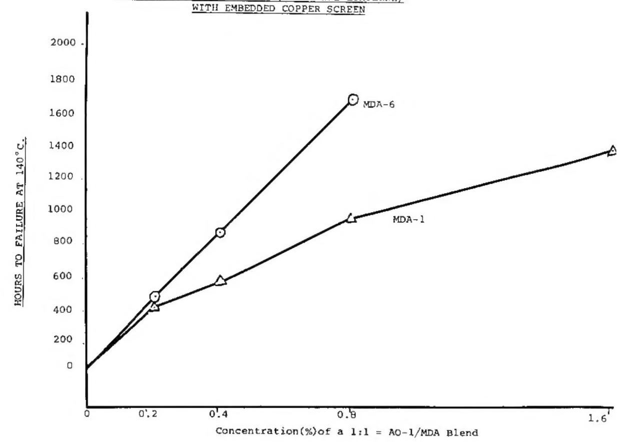

FIGURE 5
THERMAL STABILITY OF POLY(PROPYLENE-ETHYLENE)
EFFECT OF MDA - COPPER SCREEN AND WIRE

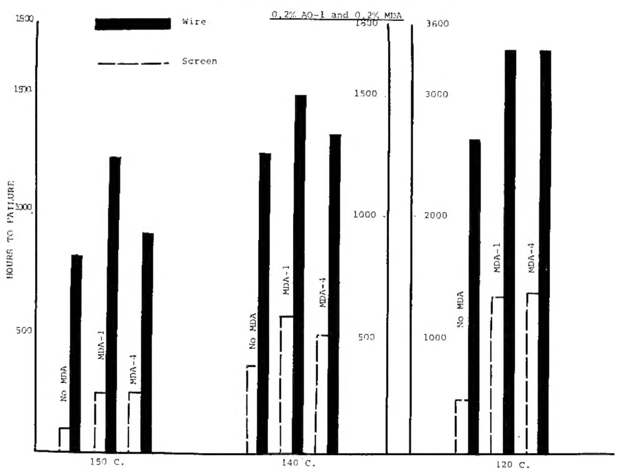

FIGURE 6
EFFECT OF EXPOSURE TO PETROLATUM/POLYETHYLENE (PJ)
FILLER ON THERMAL STABILITY OF POLY(PROPYLENE-ETHYLENE)

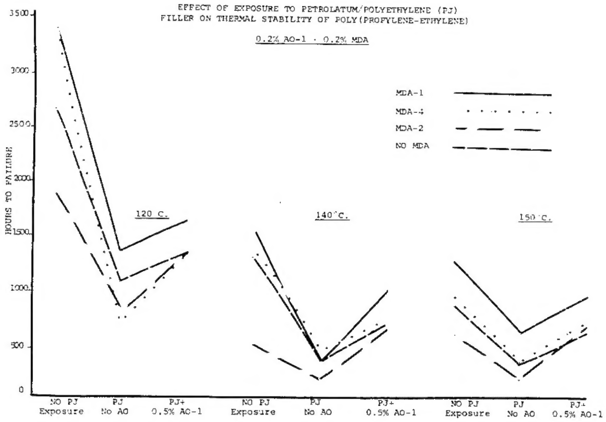

TABLE 1

EFFECT OF COPPER ON THERMAL STABILITY OF POLY(PROPYLENE-ETHYLENE)

COMPRESSION MOLDED PLAQUES CONTAINING EMBEDDED COPPER SCREEN

	HOURS TO FAILURE				
0.2% AO-1+	120°C.	140°C.		150°C.	
	Cu	No Cu	Cu	No Cu	Cu
No MDA	460	1710	360	850	100
0.2% MDA-1	1320	1870	570	760	250
0.2% MDA-4	1360	1780	500	760	250

TABLE 2

THERMAL STABILITY OF POLY(PROPYLENE-ETHYLENE)

Wire Insulation

	Hours to Failure		
0.2% AO-1 + 0.2% MDA	150°C.	140°C.	120°C.
No MDA	820	1250	2648
MDA-1	1230	1500	3368
MDA-2	570	460	1856
MDA-4	920	1330	3368

TABLE 3

THERMAL STABILITY OF POLY(PROPYLENE-ETHYLENE)
OXYGEN UPTAKE

	Hours to Failure		
	Time at 140°C for Absorption of 10 cc of Oxygen/g Polymer		
0.2% AO-1 + 0.2% MDA	Not Exposed to Filler, No Oven Exposure	Dipped in Molten Filler Containing 0.5% AO-1 and Then Exposed at 70°C for Time Indicated Prior to Oxygen Uptake Evaluation	
		250 Hours	1000 Hours
No MDA	520	160	< 18
MDA-1	550	240	190
MDA-2	450	160	< 18
MDA-4	320	210	< 18

TABLE 4

EFFECT OF ANTIOXIDANTS IN PETROLATUM
ON THERMAL STABILITY OF POLY(PROPYLENE-ETHYLENE) INSULATED WIRE

	Hours to Failure at 140°C: 0.2% AO-1 + 0.2% MDA-4 in Insulation
Not exposed to filler	1390
Exposed to filler without antioxidant	470
Exposed to filler containing 0.5% antioxidant	
AO-1	1050
AO-3	470
AO-5	520

TABLE 5

THERMAL STABILITY OF PETROLATUM

	Gardner Color 170 Hours at 140°C	Time (Hours) at 150°C for Absorption of 10 cc of Oxygen/g of Filler
No Antioxidant	9	21
0.5% Antioxidant		
AO-1	8	197
AO-2	12	-
AO-3	18	111
AO-4	8	58

TABLE 6

THERMAL STABILITY OF PIGMENTED (1.0% TiO_2) LOW DENSITY POLYETHYLENE WITH EMBEDDED COPPER SCREEN

Effect of Metal Deactivators with Various Antioxidants

Hours to Failure at 120°C.

0.1% Antioxidant + 0.1% Metal Deactivator

	No MDA	MDA-1	MDA-2	MDA-3	MDA-4	MDA-5	MDA-6
No AO	40	-	-	-	-	-	-
AO-1	230	230	230	560	528	230	1490*
AO-2	160	230	230	510	480	230	-
AO-3	110	110	110	110		110	-
AO-4	140	230	-	620	450	-	1320

* .05% AO-1 + 0.05% MDA-6 - 900 hrs.

TABLE 7

THERMAL STABILITY OF PIGMENTED (1.0% TiO_2) LOW DENSITY POLYETHYLENE

Oven Aging of Insulated Wire

	Time to Failure (hours): 110°C (aged)	90°C (uncoiled)	80°C (aged as pigtail)
0.1% AO Alone			
AO-1	620	790	1170
AO-4	570	620	620
AO-3	240	620	570
0.1% AO-1 + 0.1%			
MDA-1	400	2150	3570
MDA-3	1630	2920	5470
MDA-4	790	2460	4210
MDA-6	1580	2030	3860
0.1% MDA-4 + 0.1%			
AO-1	790	2460	4210
AO-3	240	1170	790
AO-4	740	2510	3870

TABLE 8

COMPARISON OF PIGMENTED AND NATURAL LOW DENSITY POLYETHYLENE

LDPE with Embedded Copper Screen

Hours to Failure at 120°C.

	Natural	1.0% TiO_2
No AO, No MDA	40	40
0.1% AO		
AO-1	230	230
AO-2	160	160
AO-3	110	110
0.1% AO-1 + 0.1% MDA		
MDA-1	160	230
MDA-2	230	230
MDA-3	500	560
0.1% AO-2 + 0.1% MDA		
MDA-1	230	230
MDA-2	230	230
MDA-3	500	510
0.1% AO-3 + 0.1% MDA		
MDA-1	140	110
MDA-2	110	110
MDA-3	500	110

TABLE 9

THERMAL STABILITY OF PIGMENTED 1.0% TiO_2) LOW DENSITY POLYETHYLENE

DTA in Copper Dishes at 200°C

Time to Exotherm (minutes)
0.1% Antioxidant and 0.1% Metal Deactivator

	No MDA	MDA-1	MDA-2	MDA-3
AO-1	37	39	33	52
AO-2		33		49
AO-3		23	39	27